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TYPE PALEOZOIC SECTIONS IN THE MINNESOTA VALLEY[1]

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ABSTRACT

The type sections of the St. Lawrence formation, the Jordan sandstone, the Shakopee dolomite, and the St. Peter sandstone occur in the Minnesota Valley. Additional information regarding these formations has been obtained from local well logs, and all four sections are redescribed, together with a mention of some of their more common fossils. The article does not present a redefinition and extension of the formations but merely a statement of their limits as applied by Winchell and others over a period of years. The limits are still regarded as valid.

INTRODUCTION

The newly formed Geological and Natural History Survey of Minnesota began its work in the Minnesota Valley in 1872, because of the supposed economic importance of the region. The Minnesota Valley is one of the major physiographic features of the state. It is broad, deep, and quite out of proportion to the relatively small, sluggish stream now flowing in it. The valley is, in fact, the course of River Warren, which was the outlet of Lake Agassiz during the closing stages of the late glacial period, and the River Warren in part followed a buried preglacial valley of much greater antiquity. Much of the area traversed by the Minnesota River is heavily drift-covered, but the River Warren cut through this mantle, exposing a vari-

[1] Published by permission of the director of the Minnesota Geological Survey.

able rock section which in some places must have been nearly 200 feet. With the changed conditions and the establishment of the present stream, the old valley has been partly filled by gradual sedimentation until the Minnesota River now flows 80 feet or more above the old rock floor. The rock sections, which might have been excellent, are therefore masked by river fill and by a heavy covering of glacial drift. Few, if any, of these sections as they now exist are such as should have been chosen for types in a state where excellent outcrops are common.

The oldest rocks exposed along the valley are pre-Cambrian, probably Archeozoic, but these give way to Paleozoics a short distance to the east of New Ulm; and at St. Lawrence the river has cut deep into the Cambrian, and there the first type section is located.

ST. LAWRENCE FORMATION

The village of St. Lawrence is located on the Omaha division of the Chicago and Northwestern Railway about 3 miles southwest of Jordan, Scott County. The formation, the type section of which is located there, was named from this village and from the township in which it is located.

Although the St. Lawrence is usually called a limestone or a dolomite and the drillers' log often records it as such, outcrops show that it contains a large percentage of shale and sandstone, both of which, however, are usually dolomitic. In general, it may be described as a sandy gray to brown dolomitic formation which is often shaly but may be thick bedded or even massive. The sandy dolomitic beds may alternate with sandy-greenish shale, or such shale may constitute a very important part of the formation. Glauconite is a common constituent, especially of the more dolomitic beds; and at some places this occurs in such great abundance that the rock appears green. Weathering alters the greensand, or glauconite, changing it to a rusty brown or yellow; and leaching may have removed the greater portion of the carbonates from the formation, leaving a fine-grained porous rock which passes as a sandstone.

The name "St. Lawrence limestone" was first used by Alexander

Winchell[2] in his report on the Belle Plaine region, but the formation was described by N. H. Winchell from the quarries in the N.E. ¼, Sec. 28, St. Lawrence Township, Scott County,[3] Minnesota. These quarries were opened about the year 1865 in the dolomitic beds that were discovered in the remnants of an old rock terrace about 45 feet above the river level. The rock was used in the building of a hotel and two or three houses in the neighborhood but never found a wide market. At the quarries the rock is described by Winchell as a buff to reddish- or yellowish-gray siliceous dolomite containing grains of glauconite. At some places the glauconite is said to be so abundant that it constitutes the greater part of the rock.

The following section was measured by N. H. Winchell at the Hewitt and Beason quarries and is essentially the same as that given by Alexander Winchell in his report of the previous year.

SECTION AT ST. LAWRENCE, SCOTT COUNTY[4]

No. 1. Beds 2–4 inches, with shaly partings and green specks	3 feet
No. 2. Beds 14–18 inches, hard silicious, occasionally porous from crystallization, specked with green, showing crystals of brown spar—a good building-stone	4 feet
No. 3. Somewhat ferruginous, hard and crystalline, less porous than No. 2	2 feet
No. 4. Beds irregular, specked with green, and showing green surfaces	4 feet
No. 5. Bands of greenish shale, sandy	6 inches
No. 6. Beds 2–4 inches; magnesian limestone, seen about	1 foot
Total	14½ feet

Although the total thickness of the rock quarried at the type locality is given as about 15 feet, wells in that locality are said to have penetrated 24 feet without reaching the base of the formation.

A revision or redescription of the section covering the quarries and

[2] "Report of a Geological Survey of the Vicinity of Belle Plaine, Scott County," *Minn. Senate Document* (1872), p. 10 (16-page pamphlet).

[3] "The Geology of the Minnesota Valley," *Geol. and Natural Hist. Surv. Minn., 2d Ann. Rept.* (1873) (1874), pp. 152–55.

[4] *Ibid.*, p. 153.

the outcrop in the small stream adjacent should be about as follows, if one attempts to preserve as much of the original as possible:

No. 8. Alluvium	2 feet
No. 7. Limestone, dolomitic, sandy, brown to buff, mottled with green and having partings of green shale	3 feet
No. 6. Limestone, dolomitic, siliceous, porous, buff to brown, with grains of glauconite scattered through it. Formerly quarried for building-stone	4 feet
No. 5. Limestone, dolomitic, hard, brown to pink, partly crystalline	2 feet
No. 4. Limestone, dolomitic, irregularly bedded, with glauconite	4 feet
No. 3. Shale, arenaceous, gray to green	½ foot
No. 2. Dolomite, sandy, buff	1 foot
No. 1. Shale, arenaceous, gray and thin beds of sandy dolomite	17 feet

Some of these beds in the lower part of the quarry now are partly covered, but the 16–18 feet of shale and shaly sandy dolomitic beds at the base are well shown along the small brook draining the quarry. Although not included in the original section, the reference to the thickness of the St. Lawrence in wells of the vicinity and subsequent use of the term by Winchell indicate that the shaly beds below the quarries are a part of the formation. N. H. Winchell identified the dolomitic shales in the bottom of Sand Creek at Jordan as the upper part of the St. Lawrence formation and stated that "the well of the lower brewery . . . . was dug 6 feet in sandstone and then 5 feet in this very hard limestone. Below this it was drilled 25 feet, all the way in limestone, which was thought to grow harder. . . . . All these exposures of St. Lawrence limestone in the Minnesota Valley probably exhibit its upper portion"[5] only. This is borne out by the log of the Minneapolis and St. Louis Railway well at Jordan, which, after passing through 112 feet of alluvium, penetrated 98 feet of shale and dolomite referred by Hall, Meinzer, and Fuller[6] to the St. Lawrence. As the elevation of this well location is at or near that of the St. Lawrence–Jordan contact in the nearby Sand Creek, it follows that 100

[5] "Preliminary List of Rocks," *ibid., 8th Ann. Rept.* (1880), pp. 104–5.

[6] C. W. Hall, O. E. Meinzer, and M. L. Fuller, "Geology and Underground Waters of Southern Minnesota," *U.S. Geol. Surv. Water Supply Paper 256* (1911), p. 340.

feet or more of the formation have been removed at the location by the erosion of River Warren and that the total thickness of the St. Lawrence is about 200 feet. Records of deep wells to the south show essentially the same thickness[7] of dolomitic beds at this horizon. This is the same as the thickness assigned to the St. Lawrence by Winchell and Upham in the City Water Works well No. 1 at Faribault, and checks fairly well with the assigned thickness of the formation in the wells at Merriam Junction,[8] Chaska, Minneapolis, etc. Although somewhat greater than in the sections of this formation as it crops out along the bluffs of the Mississippi River south of Red Wing, where it may not exceed 100 feet, perhaps this reduced thickness is to be explained in part by a tendency of various workers to rob the St. Lawrence of almost barren beds to build up the formation immediately below it.

In commenting on the formation at its type section, Winchell says that

> . . . . the St. Lawrence limestone was so named in the report of progress for 1873. It is the same that Prof. Irving named, in 1875, "Mendota limestone." This limestone is unfavorably exposed in the Minnesota valley. Its greatest thickness, known there, is only about 15 feet, but it seems to extend, with some shaly components, distinctly over a thickness of about 30 feet in the Mississippi valley; while, if the shaly beds with which it is associated, and into which it seems to graduate, be included under this term, it will include beds to the amount of nearly 200 feet.[9]

This is the interpretation placed on the formation by Winchell in later years, as indicated by the well log shown on page 342, in which the correlations were made and signed by N. H. Winchell and Warren Upham under date of 1910, and now on file at the Water Works office, Faribault.

The type section and beds associated with it in the type locality constitute, therefore, only a portion of the whole formation as included by Winchell and his successors on the Minnesota Geological

[7] W. H. Norton, "Deep Wells of Iowa," *Ia. Geol. Surv.*, Vol. XXXIII (1927), pp. 157, 276, 290, etc.

[8] "Geology and Underground Waters of Southern Minnesota," *op. cit.*, pp. 150, 341, and Pl. X.

[9] "Revision of the Stratigraphy of the Cambrian of Minnesota," *Geol. and Natural Hist. Surv. Minn., 14th Ann. Rept.* (1885) (1886), p. 336.

Survey. This is also the interpretation of the formation recognized by the United States Geological Survey.[10]

Some of the common fossils of the St. Lawrence are: *Dendrograptus hallianus* Prout, *Billingsella coloradoensis* (Shumard), *Lingulella mosia* (Hall), *Lingulella winona* (Hall), *Syntrophia barabuensis* (A. Winchell), *Hyolithes corrugatus* Walcott, *Agnostus disparilis* Hall, *Dikelocephalus minnesotensis* Owen, *Osceolia osceola* (Hall), *Saukia pepinensis* (Owen).

CITY WATER WORKS WELL NO. 1, FARIBAULT, MINNESOTA

No. 7. Gravel	25 feet
No. 6. St. Peter sandstone	75 feet
No. 5. Shakopee, New Richmond, and Oneota	225 feet
No. 4. Jordan sandstone	100 feet
No. 3. St. Lawrence shale	200 feet
No. 2. Dresbach (Franconia) sandstone	100 feet
No. 1. Dresbach shale and sandstone	25 feet
Total depth	750 feet

JORDAN SANDSTONE

The town of Jordan is located chiefly in Sec. 19 of Sand Creek Township, Scott County, though it spreads into the adjacent territory. It is on both the Minneapolis and St. Louis Railway and the Omaha division of the Chicago and Northwestern Railway. Sand Creek flows through the center of town, which is at the very edge of the valley of old River Warren. The sandstone, of which this is the type locality, was once extensively quarried here and undoubtedly an attractive section was exposed, but now the old quarry pits are filled by back water from the dam and the opportunity to observe the rock is limited. The old beer vaults are still available and may be entered at least during dry weather. A good outcrop is exposed at the dam. One of the upper quarries is mostly out of water, and a good outcrop occurs upstream beyond the park. When the new highway was built a few years ago, other and higher beds were uncovered, but they are not visible now.

The Jordan is, for the most part, a medium-grained, white to yellow or brown sandstone, massive to thin bedded and poorly cement-

[10] "Geology and Underground Waters of Southern Minnesota," *op. cit.*, p. 47.

ed. Some portions, however, have been sufficiently tenaceous to render it suitable for building-stone. The upper part of the formation is much coarser; and although generally gray to white, it may show colors from pink to brown. Diagonal coloration and color banding are common, but true cross bedding is also common in both the coarser and the finer sands.

The name "Jordan sandstone" was first used by Alexander Winchell,[11] but N. H. Winchell described the formation from the quarries at Jordan and the outcrop along Van Oser's creek, about 4 miles northeast of the former. The quarries at Jordan were opened during the sixties, when quantities of the rock were removed and used for local building purposes. Winchell describes the upper part of the formation as heavy bedded and coarse grained. Some parts are ferruginous but in general light in color. Below these coarse upper beds, which outcrop in the vicinity of Van Oser's Creek but not at Jordan, the rock is a fine-grained, massive, incoherent, white or buff sandstone. At the Jordan quarries the rock is generally white to buff with rusty iron stains and streaks. The bedding is usually thin to medium, and the sand is medium to fine grained. All of it is inclined to be friable. The following section, measured by Alexander Winchell,[12] was copied by N. H. Winchell[13] and given as the type section.

SECTION AT JORDAN, SCOTT COUNTY

No. 1.	Sandrock, buffish, quite ferruginous, thick bedded, seen at the mill	6 feet
No. 2.	Sandrock, ferruginous, thin and irregularly bedded, friable and distintegrating, with many ferruginous seams, crusts and concretions. In the quarry	3 feet
No. 3.	Sandrock, irregularly whitish or ferruginous, heavy-bedded, obliquely and beautifully banded with iron streaks and laminae. In quarry	12 feet
No. 4.	Sandrock, buffish, similar to No. 3, but thinner bedded. In the quarry	8 feet
No. 5.	Sandrock, hard and ferruginous above, soft, friable and buffish red below. Falls of Sand Creek	10 feet
No. 6.	Sandrock, whitish, compact. In the beer vaults, seen	12 feet

[11] "Report of a Geological Survey of the Vicinity of Belle Plaine, Scott County," *op. cit.*, p. 10.

[12] *Ibid.*, p. 9. [13] "The Geology of the Minnesota Valley," *op. cit.*, p. 149.

The contact of the Jordan with the underlying St. Lawrence occurs in the bed of Sand Creek, where several feet of the latter may be seen. Much of the upper part of the creek-bed outcrop referred to the basal Jordan is a flat pebble conglomerate of material undoubtedly derived from the St. Lawrence but probably a part of the Jordan. No one who has measured the outcrop at Jordan since the foregoing section was published has been able to find quite as much rock exposed as given in this section. Although some higher beds appear to have been uncovered during road construction a few years ago, it is very probable that there is much duplication in Nos. 4, 5, and 6 of the type section. Commenting on this, N. H. Winchell says:

> Although the foregoing section makes up a thickness of 51 feet for this sandstone as exposed at this place, the observations of the survey do not warrant the assignment of that aggregate thickness to the outcrops there. Some of the localities named being regarded as on the same geological horizon. The general uniformity of characters makes it difficult to judge how much of the bedding at one place may be included in the outcrop at another; but twenty-five or thirty feet would probably cover the thickness exposed.[14]

A revision or redescription of the section along Sand Creek and in the quarries at Jordan, together with those outcrops at Van Oser's Creek, which Winchell made part of the type section, would be as follows:

COMPOSITE TYPE SECTION OF THE JORDAN SANDSTONE

Jordan sandstone

No. 12.	Sandstone, coarse, gray to white, massive with reconstructed grains and partly case hardened. This is the top of the Minnesota Quartz Company's pit near Van Oser's Creek	8 feet
No. 11.	Sandstone, medium to coarse, massive, friable, white with rounded grains. Partly covered	14 feet
No. 10.	Sandstone, medium to fine grained, massive, white, occurring along Northwestern Railway tracks	10 feet
No. 9.	Sandstone, medium to coarse, massive, gray to white, well shown along Van Oser's Creek	8 feet
No. 8.	Sandstone, white to yellowish, covered to the top of the outcrop at Jordan but known in various wells of the vicinity	20± feet

[14] *Ibid.*, p. 149.

No. 7. Sandstone, thin to medium bedded, friable, yellow to red and brown, occurring above the Jordan quarries but mostly covered ..... 5± feet

No. 6. Sandstone, thin and irregularly iron stained, friable, white to yellow, in the upper part of the quarries ..... 3 feet

No. 5. Sandstone, irregular and massive bedded, white to buff, some of it obliquely banded and streaked with iron. This is the main part of the old quarries 12 feet

No. 4. Sandstone, medium grained, friable, white to yellow or buff, part of it cross bedded and often color banded. This rock occurs in the lower part of the quarries, at the dam or the Falls of Sand Creek, and in the old beer vaults ..... 10 feet

No. 3. Sandstone, gray to brown, partly covered near the foot of the dam ..... 1 foot

No. 2. Conglomerate, flat pebble, gray dolomitic pebbles, imbedded in a pink sandy dolomitic matrix along the bed of Sand Creek ..... 3 feet

St. Lawrence formation

No. 1. Dolomite, arenaceous, fine grained, shaly, gray to pink and purple, now partly covered and disappearing in the bed of Sand Creek at the small bridge near the hatchery and opposite the lower brewery ..... 2 feet

A complete section, such as this, must be considered the type of the formation, since Winchell included both the Jordan and the Van Oser outcrops in his original descriptions. These represent both contacts or near contacts, and there is no doubt but that he used the name Jordan to include all the sandstone lying between the base of the Oneota dolomite and the top of the St. Lawrence formation. The covered interval not observed by Winchell at the time was later extensively studied along the Mississippi River from Hastings southward, where the whole formation is exposed and there remained no unknown interval within the body of the formation.

The Jordan sandstone usually retains a rather uniform thickness of 80–100 feet; but to the south in Iowa it is very irregular, at places not exceeding 30 feet.[15] At some places there are thin lenticular beds of blue shale, especially in the lower part of the formation. These are

[15] Norton, "Deep Wells of Iowa," *op. cit.*, pp. 276, 290, etc.

in marked contrast to the usual beds of loosely cemented white sand. The upper beds may show great quantities of calcite and dolomite cementing the resistant beds which, along the Mississippi River, form the rough-faced cliff just below the Oneota dolomite high along the bluffs. This contact then becomes a very difficult one to locate.

The fauna of the Jordan is very limited and uncertain. It is a poor type of formation to retain its fossils, since it is both a loosely cemented rock and an abundant water-bearing horizon. At Jordan several poor specimens of linguloid brachiopods have been found. It seems quite probable that during the days of active quarrying at Jordan careful search would have revealed a number of fossil forms. Along the St. Croix and Mississippi rivers poorly preserved fossils are occasionally found in the lower part of the formation in the beds which Ulrich calls the Norwalk sandstone.[16] Since these are the beds which constitute the type section at Jordan,[17] that fauna probably should be regarded as typical of the formation. In some places the shaly streaks referred to in the foregoing pages carry abundant fragments of a large *Aglaspis* sp., or some related form still unidentified and one or two species of *Lingulella*. Walcott suggests that the fauna found near Devil's Lake, Wisconsin, may be Jordan,[18] and his list of fossils includes genera which appear to be the same as those found in the lower portion of this formation along the Mississippi River. Some of the genera that may be expected at least in the lower part of the Jordan sandstone are: *Lingulella* sp., *Sinuopea* sp., *Illaenurus* sp., *Osceolia* sp., *Saukia* sp., and *Aglaspis* sp.

The upper part of the sandstone usually called Jordan from St. Peter southward carries, in places, a rather extensive molluscan fauna which appears to be of post-Cambrian age somewhat resembling that of the Oneota. This fauna is especially prolific at Kasota, where eight or ten different species have been collected. Dr. Powell

[16] E. O. Ulrich, "Paleozoic Systems in Wisconsin," *Trans. Wis. Acad. Sci., Arts and Letters*, Vol. XXI (1924), p. 86.

[17] C. R. Stauffer, "The Jordan Sandstone," *Jour. Geol.*, Vol. XXXIII (1925), pp. 699–713.

[18] C. D. Walcott, "Cambrian Geology and Paleontology," *Smithsonian Misc. Coll.*, Vol. LVII (1914), p. 355.

has named these upper beds the Kasota sandstone and tentatively correlated them with the Eminence[19] of Missouri. The thickness of the Kasota sandstone is slightly greater than 6 feet, and it is separated from the Jordan by a very slight break. Above the Kasota sandstone is a bed of pale blue to green siltstone having a thickness of a few inches to 3 feet. It contains two or three species of brachiopods, probably belonging to the genera *Obolus* and *Lingulella*. Powell has proposed the name "Blue Earth siltstone"[20] for this bed. Both of these usually have been included in the Jordan sandstone. They appear to be remnants of very limited distribution, but they prevent the Oneota from being in contact with the Jordan wherever they are developed and suggest unconformity elsewhere.

SHAKOPEE DOLOMITE

The town of Shakopee is located on a rock terrace on the south bank of the Minnesota River in the northeast corner of Jackson Township, Scott County. The Chicago, Milwaukee, St. Paul and Pacific Railway and the Omaha division of the Chicago and Northwestern pass through it. In the days gone by it was the scene of active quarrying and lime manufacture. The rock cropping out here impressed the early geologists with its importance, and Winchell named it after the town, making the local quarries the type section. In general, the Shakopee is a gray to buff or brown, dolomitic limestone, massive to thin bedded, often cherty, arenaceous and frequently oölitic. In discussing it, Winchell says: "This limestone belongs to the great Lower Magnesian formation, and is the uppermost member of it."[21] In this he was quite correct, but unfortunately at the time he did not recognize the northward thinning of these formations and described the outcrop, together with the beds underlying the quarries, as Shakopee. The type section as given by Winchell[22] is as follows:

[19] L. H. Powell, "The Ozarkian Faunas of Southeastern Minnesota" (Ph.D. thesis), Univ. Minn. (1933), pp. 15–18.

[20] *Ibid.*, p. 30.

[21] "The Geology of the Minnesota Valley," *op. cit.*, p. 138.

[22] *Ibid.*, p. 140.

SECTION AT SHAKOPEE, IN SCOTT COUNTY

No. 1. Can hardly be separated from the rest, but seems more shattered and thinner bedded. It also contains some chert. It is crystalline and porous, with no regularity of bedding ..... 6–8 feet

No. 2. An irregular layer of sandstone or of very sandy limestone, used for building-stone, making some good faces; beds about 8 inches ..... 2 feet

No. 3. Rather heavier beds of hard gray limestone, of a magnesian texture and feel. These beds are sometimes cracked and checked in all directions, and pass into fine-grained patches, and then thicken again. These thin beds are not infrequently wavy or contorted within the mass. Purgatories are also common in the face of the bluff through all the parts ..... 10–12 feet

A revision of this section and combination with the log of the Shakopee Water Works well gives the following.

SECTION OF THE G. B. CONTRE QUARRY SUPPLEMENTED BY THE WATER WORKS WELL LOG AT SHAKOPEE, MINNESOTA

Shakopee dolomite

No. 13. Dolomite, pink to brown, semi-crystalline, alternating with compact buff beds, all fairly thin bedded and uneven. Fossiliferous ..... 7 feet

No. 12. Sandstone, irregular, gray and sandy gray dolomite ..... 2 feet

No. 11. Dolomite, gray to pink, fairly massive but splitting into thinner beds. These beds extend to the bottom of the quarry ..... 10 feet

No. 10. Dolomite, thin bedded, gray to pink or brown. Occurring in ditch and water hole below the quarry floor and now partly covered ..... 5 feet

No. 9. Covered interval to level of Minnesota River. In the well and partly in outcrop above the town this portion is shown to be gray to brown dolomite ... 14 feet

New Richmond ? sandstone

No. 8. Sandstone horizon suggested by line of springs along river front and found in a half dozen local private wells. Base at Minnesota River level .... 2 feet

The following rocks lie below the Shakopee dolomite and are an interpretation of the local Water Works well log.

Oneota dolomite

No. 7. Dolomite, gray to drab	31 feet
No. 6. Sand and sandy gray dolomite, water-bearing and reported as sandstone	35 feet

Jordan sandstone

No. 5. Sandstone, buff to white	100 feet

St. Lawrence formation

No. 4. Dolomites, arenaceous, with shales and sandstone	144 feet

Franconia sandstone

No. 3. Sandstone, white	95 feet

Dresbach formation

No. 2. Sandstones, gray, and gray shales	173 feet

Hinckley sandstone

No. 1. Sandstone, white and red. To the bottom of hole, 22 feet A.T.	98 feet

Winchell followed the type section by statements indicating that he regarded the quarries at Ottawa, Kasota, and Mankato as belonging to the Shakopee dolomite. This confusion was carried over a number of years, but gradually corrected and finally cleared up completely by Winchell in his report of 1886, when he said:

> The existence of the great thickness of this limestone at Shakopee rests on the uncertain testimony of the deep wells there which have penetrated it. But although the details of these wells are not obtainable so as to show the possible existence or non-existence in this limestone of any thin beds of sandrock, yet they unite with sufficient testimony to demonstrate that there is under Shakopee village, extending far below any rock exposed in the quarries, a stratum of limestone, or what the well-drillers denominate wholly limestone, that is entirely comparable to that in the bluffs at and near Hastings, and should be parallelized with it. The quarries at Shakopee involve only from 15 to 20 feet of the uppermost layers of this stratum, and to these layers the term *Shakopee* should be applied and only to these, or at most, to those underlying layers that extend downward to the thin sandstone which is known to exist, with more or less persistence, in this great formation about 25 feet below its top.[23]

Most of the deep wells at Shakopee give no direct evidence of this sandstone. Much of the formation, however, may be somewhat are-

[23] "Revision of the Stratigraphy of the Cambrian of Minnesota," *op. cit.*, p. 327.

naceous, and a 5- or 10-foot sandstone stratum might easily be penetrated but not recorded by the driller. The line of springs at or near river level at Shakopee and eastward for a mile or more suggests the presence of such a water-bearing rock. Moreover,

> A short distance above Shakopee, at the Louisville limekilns, and between them and the river, this limestone underlying the city of Shakopee is significantly divided into two parts, each part extending horizontally over considerable distances forming a marked terrace-flat. These parts exhibit different outward lithological aspects and intimate stratigraphic structure. The upper one is that which is wrought for quick lime at the limekilns at Lousiville. . . . . The thickness of lime rock involved in this upper terrace of Louisville cannot be seen to exceed 30 feet. . . . . The stone is very irregular in its bedding, and like the real Shakopee limestone, answering to the descriptions, given before, of the exposures at Shakopee, at (or near) Quincy in Winona County, and at Northfield. . . . . These rough upper beds swing back from the river in their line of strike, a little to the northeast of Merriam Junction, and are not known to occur in outcrop again, in their entirety, in the Minnesota valley. These are the beds which properly and correctly represent the Shakopee limestone.[24]

Mr. J. A. Wilder's well, located in the southeast edge of Shakopee, gives some interesting information on the possible limitations of the Shakopee as a formation. The following is a log of that well:

LOG OF J. A. WILDER'S WELL AT SHAKOPEE

(*River fill*)	
Soil	2 feet
Yellowish stratified clay	5 feet
Sand and gravel, interstratified, coarsest below	38 feet
(*Shakopee*)	
Hard limestone	61 feet
(*New Richmond ?*)	
Quicksand and sandstone, plenty of water	2 feet
(*Oneota ?*)	
Hard, cherty limestone	4 feet

A number of other wells in this vicinity show a similar section and obtain water from a sand horizon which at some places is 5 feet thick. Commenting on the preceding well log, Winchell says:

> The thin sandstone stratum mentioned in Mr. Wilder's well, underneath 61 feet of limestone, and underlain by a hard cherty limestone, is the representa-

[24] *Ibid.*, pp. 328–29.

tive of the New Richmond sandstone. It is probable that the horizon at which the other wells get water and sand was in the same sandstone, this being, at the place where these wells are located, about the level of the water of the Minnesota.[25]

The Shakopee dolomite is overlain by the St. Peter sandstone, and it is very clear that Winchell knew absolutely the limits of the formation when his final report was made.[26] The upper surface of the Shakopee appears to be an unconformity, and possibly the lower limit as well.[27] Hence the thickness of the formation is somewhat variable. At Minneapolis well logs indicate about 65 feet of Shakopee dolomite, but to the south of the type locality it appears to increase enormously, so that in Iowa it often approaches 200 feet in thickness.[28] The whole Lower Magnesian or Prairie du Chien series may exceed 450 feet. Owing to the occurrence of thin layers of sandstone in the lower part of the Shakopee and in the upper part of the Oneota, there is grave doubt about the possibility of identifying the sandstone which Winchell recognized as the New Richmond. Sardeson has thrown further doubt on this identification by finding fossiliferous Shakopee dolomite interbedded with the upper sand at New Richmond.[29] It is certain, however, that there is a 25-foot to 40-foot sandstone formation lying between the Oneota and Shakopee as recognized in southern Minnesota and that this sandstone increases in thickness to 80 or 100 feet in parts of Iowa.[30] This is the formation meant by the term "New Richmond sandstone" as it is commonly used by the Geological Survey in Minnesota. Whether the name should be recognized in Minnesota or whether it is properly applied in many well logs is quite another matter.

The fauna of the Shakopee is seldom abundant and usually consists of poorly preserved specimens. The best material has been found during active quarrying or excavation of the formation, but

[25] *Geology of Minnesota*, Vol. II (1888), p. 126 n.

[26] "Revision of the Stratigraphy of the Cambrian of Minnesota," *op. cit.*, pp. 334–36, and *ibid.*, pp. xxi–xxii.

[27] Ulrich, "Paleozoic Systems in Wisconsin," *op. cit.*, pp. 101–2.

[28] Norton, "Deep Wells of Iowa," *op. cit.*, pp. 123, 275, 289, 309.

[29] F. W. Sardeson, "Type Outcrops of the Minnesota River Valley," *Pan.-Amer. Geol.*, Vol. XLI (1924), p. 115.

[30] Norton, "Deep Wells of Iowa," *op. cit.*, pp. 217, 275, 360, etc.

fossils can be found even in the weathered outcrops. At Shakopee Sardeson found the following fauna:[31] *Hormotoma argylensis* (Sardeson), *Raphistoma ruidum* Sardeson, *Subulites exactus* Sardeson, *Eurystomites kelloggi* (Whitfield), *Endoceras consuetum* Sardeson. In addition to these there has been found a diminutive fauna of an entirely new species in the oölitic cherts of this formation. The species have not as yet been described.

The upper part of the formation carries some of the same species as those mentioned by Sardeson and a few others of which several are still unidentified trilobites. *Cryptozoon minnesotense* N. H. Winchell is probably found at several horizons in the formation but is more common in the lower part. It can be found a short distance up the river from Shakopee and abundantly in the lower part of the formation at Cannon Falls. Sardeson states that the total known fauna consists of twelve species.[32] Very little recent work seems to have been done on the Shakopee fauna, and the field is not an attractive one from the type of material likely to be encountered; but it is entirely possible that persistence will be rewarded by many new forms. Fragments enough have been encountered to indicate that some of these should be well preserved.

ST. PETER SANDSTONE

The Minnesota River was formerly called the St. Peter's, and from the outcrops near its mouth the St. Peter sandstone was named. The type locality is at Fort Snelling, and the type section is that at the bluff where the Minnesota River joins the Mississippi River. The St. Peter is a white, friable sandstone usually without sufficient calcareous material to act as a cement; hence it can frequently be scooped up from the outcrop with bare hands. The ease with which the loose sand may be removed has been responsible for the formation of many water falls in the Minneapolis–St. Paul area, where the Platteville limestone acts as the resistant layer from the ledges of which the water tumbles. Beneath these cities, however, it is much

[31] F. W. Sardeson, "The Fauna of the Magnesian Series," *Bull. Minn. Acad. Nat. Sci.*, Vol. IV (1896), p. 94; and "Shakopee Dolomite and its Cone-Domes," *Pan.-Amer. Geol.*, Vol. XLV (1926), p. 31.

[32] "Shakopee Dolomite and its Cone Domes," *loc. cit.*, p. 32.

tunneled, and the walls stand without reinforcement. In South St. Paul a portion of the sand is well cemented and the rock is exceedingly resistant. Concretions of pyrite are often common, especially in the upper part; and the weathering of these along the outcrops produces a yellow or brown stain. The grain of the sand is medium to fine, well rounded, and frosted. Below the middle of the formation some of the deep wells in St. Paul strike a fine gray silt 10–30 feet thick which is almost impervious to water. This is usually reported as a clay or shale, but an examination of the samples by Dr. Thiel shows it to be fine quartz sand with little or no clay.

In Owen's original description of the formation, he states that the sandstone "is remarkable for its whiteness. When examined by the magnifier, it is found to be made up of grains of limpid and colorless quartz."[33]

The St. Peter sandstone is "designated on the sections as Formation 2c, and superimposed on the Lower Magnesian limestone. . . . . It is the rock which . . . . forms the base of the bluffs at the St. Peter's. It constitutes also the lower nineteen feet of the chute of the Falls of St. Anthony."[34] In discussing the St. Peter sandstone of Iowa, James Hall says: "Being also conspicuously developed at the mouth of the St. Peters river, Dr. Owen has given it the name of St. Peters sandstone."[35]

"The thickness of F.2c is from forty to ninety feet, its greatest measured thickness being at Fort Snelling, near the St. Peter's."[36] No detailed section of this sandstone was measured by Owen, but several horizontal sections passing through Fort Snelling or the mouth of St. Peter's (Minnesota) River are given. Section No. 1 gives a "Series of sections on the Mississippi between the Mouth of the Wisconsin and the Falls of St. Anthony." It shows a section at Fort Snelling in which the Trenton (Platteville) is given a thickness of 25

[33] D. D. Owen, "Formations of the Upper Mississippi and Its Tributaries, Belonging to the Silurian Period," *Rept. Geol. Surv. Wis., Ia. and Minn.* (1852), p. 69.

[34] *Ibid.*, p. 69.

[35] "Geology of Iowa: General Reconnaissance," *Rept. Geol. Surv. State of Ia.*, Vol. I., Pt. 1 (1858), p. 54.

[36] "Formations of the Upper Mississippi and Its Tributaries, Belonging to the Silurian Period," *op. cit.*, p. 71.

feet and the underlying St. Peter sandstone 100 feet. The following is a recently constructed section at the type locality of the St. Peter sandstone:

TYPE SECTION OF THE ST. PETER SANDSTONE AT FORT SNELLING, MINNESOTA

Platteville limestone

No. 8. Limestone, dolomitic, blue to buff, fossiliferous... 25 feet

Glenwood beds

No. 7. Shale, soft, argillaceous and arenaceous, gray to greenish..... 3 feet

St. Peter sandstone

No. 6. Sandstone, yellowish to brown, iron-stained..... 8 feet

No. 5. Sandstone, poorly cemented, medium to fine grained, massive, white, partly covered at the base 65 feet

No. 4. Sandstone, white, covered but partly shown in excavations for the Mendota Bridge piers adjacent to the cliff..... 25 feet

No. 3. Silt, siliceous, blue reported as a shale in the Mendota well..... 30 feet

No. 2. Sandstone, white, shown in some of the excavations for piers and encountered in the Mendota well. Elevation of the St. Peter–Shakopee contact in the excavations for bridge piers, 613.4 feet A. T. (U.S. Army Eng.)..... 35 feet

Shakopee dolomite

No. 1. Dolomite, gray to brown, encountered in the bottom of excavation for pier..... 1 foot

The central piers of the Mendota Bridge at Fort Snelling show 90 feet of river filling at the mouth of the Minnesota River. All but one of the holes for those piers encountered St. Peter sandstone, the bottom of the one being on Shakopee dolomite. From this it is safe to assume that the St. Peter includes all of the outcropping sandstone to river level and 90 feet below it. The deep wells in Minneapolis and St. Paul show a thickness ranging from 150 to 165 feet. At Rochester, however, the deep well shows only 92 feet, and that thickness is still further reduced to the south in Iowa, where it may not exceed 50 feet.[37] The surface on which the St. Peter sandstone was

[37] Norton, "Deep Wells of Iowa," *op. cit.*, pp. 217, 275, 309, 322, etc.

deposited is notorious for its irregularity. It thus happens that nearby wells may show marked differences in thickness for the formation.

The lower contact of the formation is seldom shown, owing largely to the readiness with which the St. Peter crumbles to a loose sand. Wherever that contact has been uncovered, as, for example, along Highway 20 south of Preston, Minnesota, it has soon been obscured in the same manner. It has been found, however, to be a rough and uneven surface of dolomite on which the sand rests without transition, and the contact is regarded as a disconformity.[38]

The St. Peter sandstone is rarely fossiliferous. Some geologists regard large portions of it as of eolian origin. Very little, if any of it, however, shows typical dune structure. It is one of the great water-bearing formations of the state and of adjacent territory. In much of Minnesota its importance as an aquifer was even greater when it was under greater cover, as must have been the case in preglacial time. Such sandstone, even if originally quite fossiliferous, might lose all traces of its fossils by solution because of the constant passage of water through the porous beds. It appears that even the cement between the sand grains has disappeared through the agency of circulating ground water. Slight movements of the sand grains are thus possible, closing completely the fossil molds that may have been left by the solution of shells; and over wide areas the resulting bed may be devoid of all trace of its fauna. A few fossils, however, have been found in the sandstone at favored places, such as South St. Paul; and among them are forms sufficiently well preserved for description. Some of the more common forms are: *Ctenodonta novicia* (Sardeson), *Cyrtodonta descriptus* (Sardeson), *Cyrtodonta dignus* (Sardeson), *Modiolopsis contigua* Sardeson, *Modiolopsis gregalis* Sardeson. *Modiolopsis litoralis* Sardeson, *Vanuxemia fragosa* (Sardeson), *Hormotoma* sp., *Ophileta fausta* Sardeson, *Platyceras vetulum* Sardeson, *Pleurotomaria aiens* Sardeson, and *Orthoceras minnesotense* Sardeson.

This is an assemblage of marine forms occurring well within the formation; and its presence suggests the marine origin of the sand-

[38] C. L. Dake, "The Problem of the St. Peter sandstone," *Mo. School of Mines, Bull. 6* (1921), pp. 98, 99; E. B. Branson and M. G. Mehl, "Conodont Studies," *Univ. Mo. Studies*, Vol. VIII (1933), p. 20.

stone containing it, although at other places some portions of this same formation may be of eolian origin.

SUMMARY

It may be seen from the preceding pages, that the St. Lawrence formation, the Jordan sandstone, the Shakopee dolomite, and the St. Peter sandstone, which have their type sections in the Minnesota Valley, are much more inclusive as used by Winchell than might be supposed by a visit to the places from which these formations derive their names. Though in nearly every case it is possible to obtain a fair idea of the formation and of its approximate thickness by the aid of nearby well logs, few contacts are actually exposed, and large portions of the formation remain covered at the type locality. Considering the excellence of the outcrop of all these formations in other parts of the state, it is unfortunate that the work of the old Geological and Natural History Survey was started in the Minnesota Valley. The names derived from that region, however, are so well and so generally known that now they cannot be abandoned. These names have been correctly fitted to the best sections of the state and have been properly used for nearly half a century. A few minor changes have been made in the geological column representing the formations of Minnesota, but they affect only slightly, if at all, the formations herein discussed. Subdivisions of such formations as the St. Lawrence or the Jordan may be recognized, but there has been no intention of redefining the formations which derived their names from the Minnesota Valley. Rather have the known facts been brought together and the formations themselves strengthened in their position of leadership.

The discovery of the fauna in the sandy beds on top of the Jordan and formerly included with it is not new, but the tentative correlation by Powell of that fauna with the Eminence of Missouri is new and raises the question whether the "Kasota sandstone" shall be recognized as a Minnesota formation. Perhaps the same may be said of the "Blue Earth siltstone," since it also contains fossils. In general, however, the lithology and fauna of each of the formations, having its type section in the Minnesota Valley, is well known. It is probable that the faunae of some or all of the formations constituting

the St. Croixian series are not absolutely and mutually exclusive. This is certainly true of the Franconia and St. Lawrence and may be equally true of the latter and the lower part of the Jordan. The great difficulty in correlation over rather extensive areas of Upper Cambrian, however, is the lack of fossils at one place and their presence at another in beds which have every other appearance of being at the same horizon. The group of fossils given as characteristic or common for any one horizon of the St. Croixian series, therefore, may be difficult to find, but they cannot be neglected.

DEPOSITS OF POSSIBLE *NUÉE ARDENTE* ORIGIN IN THE CRATER LAKE REGION, OREGON[1]

BERNARD N. MOORE
U.S. Geological Survey

ABSTRACT

Recent pumice deposits which had their origin in a crater of old Mount Mazama are described and their origin discussed. The chemical and mineralogical composition show no specially interesting features, but field relations and mechanical analyses suggest different modes of origin for the two types recognized. The younger deposit belongs to a normally projected type, though mechanical analyses suggest that sorting by air currents has played a less important rôle here than is usually considered the case in such deposits. The older pumice, judged from the sorting and other features, has apparently had an entirely different origin, and is regarded as the product of *nuées ardentes*, or "burning clouds," which distinguish the Pelćean type of eruption. Information about Pelćean eruptions is briefly summarized, and the characteristics of deposits of *nuées ardentes* are compared with those of the Crater Lake material.

INTRODUCTION

Since the appearance of the masterly analysis by Fenner[2] on the mode of origin of the tuff deposits of the Valley of Ten Thousand Smokes, there has been a constantly increasing mention in geologic literature of *nuées ardentes* (eruptions similar to that of Mount Pelée in 1902) and their deposits, but without much attention to criteria for recognizing deposits of such eruptions. In the summer of 1931 during an investigation of the non-metallic mineral resources of eastern Oregon by the U.S. Geological Survey in co-operation with the Oregon State Mining Board, about six weeks were devoted to a study of the lump pumice deposits of the Oregon Cascades. As a result of this study it was found that there were fewer pumice deposits of Recent age in this region than had previously been supposed and that by far the greatest amount of pumice in these Recent deposits had come from ancient Mount Mazama, the predecessor of the crater now occupied by Crater Lake. One of these deposits possesses characteristics which appear to represent *nuées ardentes;* the others are apparently products of normal eruption.

[1] Published by permission of the director of the U.S. Geological Survey.

[2] Clarence N. Fenner, "The Origin and Mode of Emplacement of the Great Tuff Deposit of the Valley of Ten Thousand Smokes," *National Geog. Soc. Contr. Tech. Papers, Katmai Ser.*, No. 1 (1923).

Excellent treatments of the general geology of the region are to be found in papers by Diller[3] and Russell,[4] who have described the post-glacial pumice sheets of the region, but who have given no particular attention to their mode of origin, probably because Lacroix's paper[5] on the eruptions of Mount Pelée had not appeared at the time of preparation of their reports.

RECENT PUMICE SHEETS OF THE CRATER LAKE REGION

In the vicinity of Crater Lake there are two extensive sheets of pumice of Recent age. These blanket an area of about 3,500 square miles to the east of the Cascades, but west of the crest they have been largely removed by erosion (Fig. 1).

OLDER PUMICE

The older of the two pumice sheets forms an irregularly shaped area which nearly encircles Crater Lake, though absent from the uppermost slopes of the crater as well as from the mountainous country to the south. In the area shown on the map it does not form a continuous blanket, but the distribution is rather regular over the flats and valleys. The presence of the material on some ridges and in some of the steeper valley bottoms and its absence in others suggest that conditions of deposition as well as erosion have affected the areal pattern.

The thickness of the pumice varies greatly, not only because of erosion since its deposition, but also because of the irregularities of the surface on which it was deposited. In the terraces along Rogue River the pumice is as much as 60 feet thick and contains many charred logs. On the road from Beaver Marsh to Diamond Lake and just west of the summit of the Cascades, more than 100 feet is exposed. Eastward toward Klamath Marsh the material gradually thins, though at Lonroth coarse pumice, with lumps as much as 3 feet in diameter, is exposed in a railroad cut 10 feet deep. Klamath

[3] J. S. Diller and H. B. Patton, "The Geology and Petrography of Crater Lake National Park," *U.S. Geol. Surv. Prof. Paper No. 3* (1902).

[4] I. C. Russell, "Preliminary Report on the Geology and Water Resources of Central Oregon," *U.S. Geol. Surv. Bull.*, No. 252 (1905).

[5] A. Lacroix, "La Montagne Pelée et ses Eruptions" (Paris, 1904).

Marsh contains none of this pumice, and no trace of it is found in the region to the east of the marsh.

No recognizable sorting of the pumice is found in any of the localities studied, and still more striking is the lack of variation of

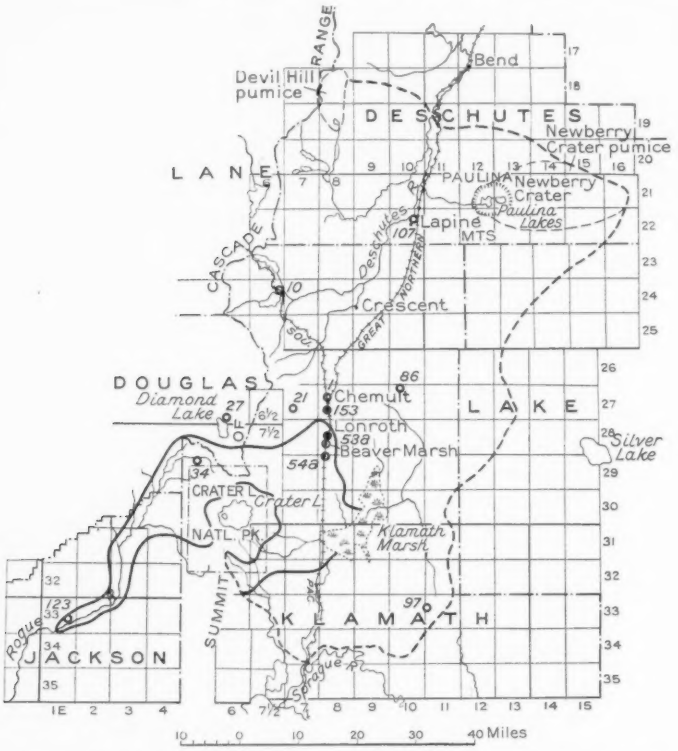

FIG. 1.—Distribution of pumice sheets of Crater Lake region, Oregon. Heavy dashed line indicates recognizable extent of younger pumice east of Cascade Range, and solid line the approximate area over which the older pumice occurs. The more recent deposits of Devil Hill and Newberry Crater are shown by light, dashed lines, but are not described in this article. Numbered circles refer to localities of samples mentioned in text.

coarseness with distance from the crater. Material from the northeast edge of the sheet near the railroad station of Lonroth is as coarse

as that near the crater. Another fact very apparent in the field is the lack of "accidental" or foreign material in the pumice. With the exception of the charred logs mentioned, no material except pumice and other products apparently of the same magma has been found in the deposit at any of the localities studied.

The pumice itself is composed mainly of finely vesicular or even fibrous glass. A small percentage of phenocrysts of plagioclase (oligoclase-andesine), hornblende, and magnetite is present, with occasional grains of hypersthene and augite. Vesicles which range from 2 mm. to 50 mm. comprise 10 to 50 per cent of its volume. The walls of these vesicles resemble nests of coiled glass filaments from which occasional phenocrysts protrude.

The finer particles are of glass and of grains of the minerals mentioned as forming phenocrysts in the pumice. Some of the glass grains are sharply angular; whereas others are striated, broken filaments. The feldspar grains have ferromagnesian inclusions, and all of the minerals have included magnetite. Hornblende in brilliant black prisms is the preponderant ferromagnesian mineral. Hypersthene occurs as long, slender, amber prisms; and the augite as green, glassy prisms. Although the material above 2 mm. consists dominantly of pumice, that from 1/8 mm. to 2 mm. consists largely of non-vesicular glass and mineral grains. Below 1/8 mm. the particles are mainly fragments of glass. Oblate spheroidal particles are occasionally found which have radiating cracks on each side and apparently represent droplets of fused glass which were expelled at the same time as the pumice and which cooled after eruption.

In several localities, notably the region to the northwest of Crater Lake, brilliant hornblende phenocrysts constitute as much as 50 per cent of the volume of the pumice. This is believed to mean that there was segregation in the magma before eruption.

An analysis of a typical sample of the lump pumice has been made in the chemical laboratory of the Geological Survey, with the results shown in Table I.

YOUNGER PUMICE

An extensive deposit of granular pumice covers the northern part of Klamath County, the southern part of Deschutes County, and the northwestern corner of Lake County, as well as a narrower strip

along the west side of the crest of the Cascades. The approximate areal extent of material pure and coarse enough to be regarded as granular pumice may be differentiated from that of the pumiceous soil (Fig. 1). Though later basaltic flows and cones are found in this area, particularly in the northernmost part, and also areas on the steeper hillsides from which the pumice has been removed by erosion, the region as a whole is effectively covered by a uniform layer of pumice about 6 feet thick at the contact with the older pumice, but only 1 foot thick at the boundary as mapped. In several

TABLE I

ANALYSIS OF OLDER LUMP PUMICE, SEC. 17, T. 28 S., R. 8 E.
(J. J. FAHEY, ANALYST)

SiO_2	69.50	Na_2O	4.78
TiO_2	0.41	K_2O	2.18
Al_2O_3	15.18	P_2O_5	0.21
Fe_2O_3	1.24	CO_2	none
FeO	1.42	H_2O	2.51
MnO	0.03	Total	100.37
MgO	0.83		
CaO	2.08		

places, particularly along the southern shores of Klamath Marsh, in the vicinity of Chemult, and north of Diamond Lake, drifts of pumice are seen which are as much as 40 feet thick.

The pumice composing this deposit varies in texture from fine to coarsely granular but may be recognized everywhere in the region by its light color, its sorting, and its peculiarly shaped particles. Over the entire region it is uniform in composition, but the coarseness of the particles decreases uniformly toward the edge of the sheet.

The granular pumice is composed of two fractions—lumps of true pumice and mineral grains. Phenocrysts, amounting in general to less than 5 per cent in volume, are composed of glassy plagioclase, prismatic hypersthene, augite, and hornblende crystals. The shape of the pumice grains is very irregular. Though they are roughly round, the walls of the broken vesicles protrude and produce a deeply pitted surface. Accidental material—fragments of andesites and basalts from the crater walls—is present in small amounts.

Mineral grains form the greater part of the material between 1/8

mm. and 2 mm. in diameter. The feldspars are broken crystals of oligoclase-andesine. The dominant ferromagnesian minerals are hypersthene in amber, euhedral prisms, and green, glassy augite prisms. All contain large amounts of included magnetite. There are also small amounts of black hornblende and fragments of foreign lavas.

The analysis of a sample of the lump pumice from a locality near Chemult, as made in the laboratory of the Geological Survey, is given in Table II.

TABLE II

ANALYSIS OF SAMPLE OF YOUNGER PUMICE NO. 1, SEC. 8, T. 27 S., R. 8 E. (J. J. FAHEY, ANALYST)

SiO_2	68.56	Na_2O	5.18
TiO_2	0.58	K_2O	2.47
Al_2O_3	14.22	P_2O_5	0.10
Fe_2O_3	1.42	CO_2	none
FeO	1.49	H_2O	3.32
MnO	0.03		
MgO	0.83	Total	100.55
CaO	2.35		

RELATIONS OF THE PUMICE SHEETS

In the region south of Chemult the contact between the younger and older pumice sheets may be studied over long distances. The granular pumice lies above the more rudely sorted material and is therefore clearly younger. Because of the looseness and coarseness of particles in the two layers of pumice, it is impossible to tell from the contact itself whether they are conformable or disconformable. The similarity in chemical and mineralogical composition and in weathering suggests that they were erupted from the same magma and are consequently of nearly the same age.

No traces of the older pumice have been found north of the contact shown, with the exception of a few localities near Chemult. In the quarry southeast of that town (Locality 153), the granular pumice rests upon a coarse, red, volcanic ash believed to represent the older pumice; and a similar ash occurs in the bottom of the railroad cut east of Locality 1. In other localities within a few miles of the contact the older pumice is absent and the younger pumice rests directly upon lavas or alluvium. The absence of the older pumice at

all other localities studied might suggest removal by erosion. If this were true, the erosion must have been highly selective to remove the deposits over vast flat-lying areas and leave them in other places on steep slopes. It is believed, however, that the deposits were laid down only over essentially the area now occupied by them, a supposition which is in accord both with the field evidence and the mode of origin to be developed subsequently in this article.

The area mapped as granular pumice (Fig. 1) represents the extent of recognizable occurrences of this material. Beyond its borders pumiceous soil is found for many miles to the east; and in the northeastern part of the state, in Wallowa and Baker counties, beds of white volcanic ash which possibly may represent the finer portions of this sheet may be found in sheltered valleys. From the region immediately surrounding Crater Lake the sheet has been removed by erosion.

ORIGIN OF THE PUMICE

Chemically and mineralogically the two types of pumice show no particularly distinctive characteristics, but their relative freshness permits a rather detailed textural study which sheds some light on their mode of origin. Mechanical analyses have been made of nineteen specimens of older pumice and of 61 samples of the younger pumice. These analyses were made by sifting the pumice in a "Rotap" machine (a device designed to rotate and at the same time tap the sieves, thereby insuring efficient sifting). It was necessary to compromise upon a length of time for sieving between that necessary for consistent results usually regarded as at least 10 minutes and the very short time required to avoid appreciable breakage of the pumice granules. All samples were sifted 2 minutes, but in even this time from 1 to 3 per cent of the sample was reduced to fragments below 1/8 mm. in the younger pumice by abrasion of the larger particles during sifting. These fines have been left out of the computed results, but the other size ranges in both pumice types are in error by several per cent. This error, however, is not large enough to affect the qualitative results based on the analyses.

Typical diagrams of the sorting of the older pumice (Fig. 2) show that this type must have had a considerably different mode of origin from that of the younger pumice (Fig. 3). The older pumice is very

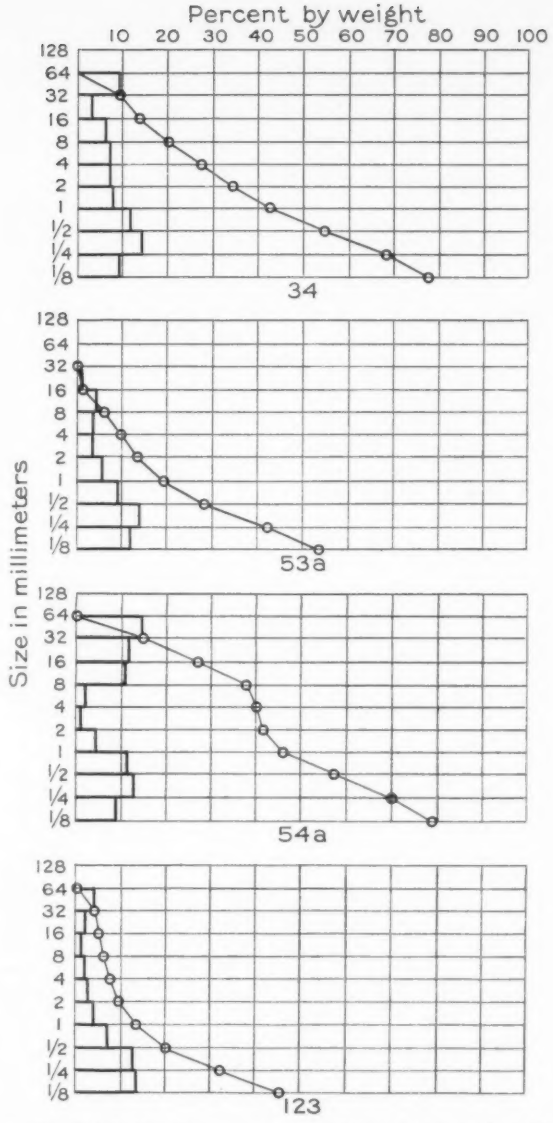

FIG. 2.—Size-distribution diagrams of finer portions of older pumice of Crater Lake region. These diagrams show the sorting of typical specimens of this material. The analyses have not been carried out for material finer than $\frac{1}{8}$ mm. in diameter. The curves are "cumulative curves" and show the percentage of the total sample retained on screens of any particular fineness. The histograms show the percentages of material passed by one screen and retained on the next finer.

poorly sorted; but if to the figures given were added the size fractions below 1/8 mm. and those up to 1024 mm., the lack of sorting would be still more striking. In most localities studied, from 25 to 75 per cent

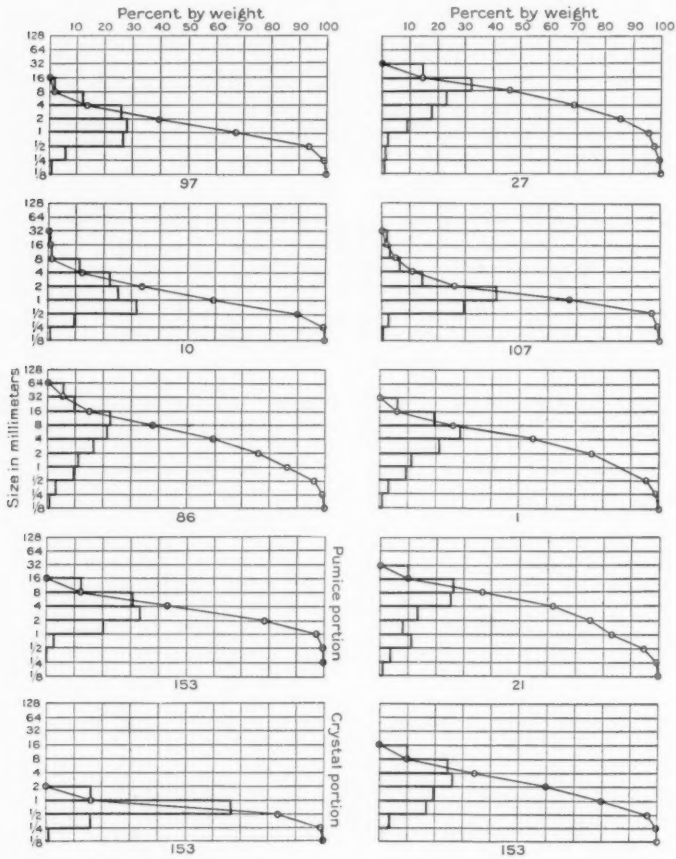

FIG. 3.—Size-distribution diagrams of younger pumice of Crater Lake region

of the bulk of the material was above 64 mm. in diameter, with large amounts ranging from 128 mm. to 1024 mm.

The younger pumice is much better sorted than the older pumice

(Fig. 3). It will be noticed that in some samples (No. 21, Fig. 3) there is a secondary maximum in the $\frac{1}{2}$–1 mm. or 1–2 mm. size range, and in all cases an unexpected tailing-out of the finer fractions. This is due to the fact that during eruption of this pumice considerable numbers of the crystal grains separated from their matrix and because of their greater density settled with the larger-sized pumice particles. Thus any given sample contains two materials—one pumice grains and the other crystals and crystalline fragments—each of which has been well sorted, but which, on settling together, produce a material not apparently so well sorted.

TABLE III

Size Range in Mm.	Original Analysis (Per Cent by Weight)	Pumice Fraction (78.9 per Cent of Total) (Per Cent by Weight)	Crystal Fraction (21.1 per Cent of Total) (Per Cent by Weight)
8–16 mm.	9.9	12.6	.....
4–8 mm.	24.2	31.0	.....
2–4 mm.	26.0	33.3	.....
1–2 mm.	19.2	20.1	16.3
$\frac{1}{2}$–1 mm.	16.8	2.8	66.9
$\frac{1}{4}$–$\frac{1}{2}$ mm.	3.6	0.2	15.8
$\frac{1}{8}$–$\frac{1}{4}$ mm.	0.3	.....	1.0
Total	100.0	100.0	100.0

For example, when Sample 153 was examined and the different constituents of the various fractions separated, it was found that pumice formed 85 per cent of the 1–2 mm. fraction, 13 per cent of the $\frac{1}{2}$–1 mm. fraction, 6 per cent of the $\frac{1}{4}$–$\frac{1}{2}$ mm. fraction, and 40 per cent of the 1/8–1/4 mm. fraction. The high percentage of pumice in the 1/8–1/4 mm. fraction is believed to have been caused by the breaking-down of larger particles by sifting and has therefore been omitted from consideration. Both the composition of the pumice fraction, amounting to 78.9 per cent by weight of the total sample, and the crystal fraction have been recomputed to a basis of 100 per cent, with the results given in Table III. These analyses have been plotted as shown in Figure 3, Nos. 153, 153—Crystal Portion, and 153—Pumice Portion. If similar treatment were given the other analyses,

it could be shown that this material is not so poorly sorted as may at first appear.

For comparison a diagram modified from Wentworth[6] is reproduced (Fig. 4) to show sorting of the type he considers typical of projected pyroclastic deposits. Though this diagram differs from the diagrams of both sets discussed, it has resemblances to some of those illustrating the younger pumice of Crater Lake (Fig. 3, 107). Wentworth[7] describes the sorting his material approaches as follows:

> This composition appears to be due to a process of winnowing, whereby at any point there fall all the coarser fragments attaining that distance from the vent and progressively lesser parts of finer grade. The sharp upper limit of sizes of the fragments is due to the completeness with which all coarser material has settled out close to the vent and the long tailing out of finer grades is due to settling out of small parts of the finer débris from the lower air currents, and is analogous to incomplete washing in a settling type of elutriator whereby the coarse grade sought is contaminated by progressively lesser amounts of the finer and slower settling grades. Similar sorting action takes place in streams and ocean currents but perhaps rarely under so simple and favorable conditions as in the case of these ash deposits.

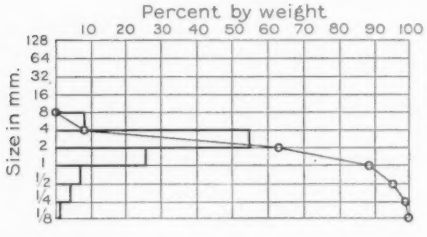

FIG. 4.—Idealized composition of some Hawaiian ash (after Wentworth).

As stated by Wentworth, pyroclastic deposits of material thrown into the atmosphere by volcanic action are usually thought to be sorted by air currents and consequently are better sorted than most sediments. This, however, may not be so for the coarser types of material. As shown by the younger pumice, the greater part of such material is nearly evenly distributed over two or three sizes (Fig. 3, 97). The velocity of the lateral air currents during an eruption is usually rather low, judging by the rather even circular or elliptical region covered by such pumice deposits around their point of origin. With low velocities of air the rate of settling would have but little

[6] C. K. Wentworth, "Pyroclastic Geology of Oahu," *Bernice P. Bishop Mus. Bull. 30* (1926), Fig. 25.

[7] *Ibid.*, p. 96.

to do with sorting of material much above $\frac{1}{2}$ mm. in diameter. If all particles were expelled during an eruption at the same trajectory, their distance of flight would be proportional to the velocity with which they were expelled or inversely proportional to the diameter of the particles if the same pressure were considered to act on small and large particles alike and if the particles have the same density. Under this premise the sorting should be perfect, other conditions being equal, if all particles were expelled at the same angle to the horizontal. Actually, however, the particles are projected in all directions, and wind resistance of particles of different sizes and shapes must be considered together with the effects of air currents and the possible rocket-like behavior of particles due to emission of gases during flight. On the whole, the degree of sorting exhibited by the younger Crater Lake pumice comes well within the limits to be expected from material ejected during a normal volcanic eruption. The sorting of the older pumice, is, however, plainly of a different type—a type suggestive of the so-called "Peléean" eruptions.

PELÉEAN ERUPTIONS

The work of Lacroix,[8] Anderson and Flett,[9] and Fenner[10] on the eruptions of Pelée, La Soufrière, and the Valley of Ten Thousand Smokes furnishes much valuable information on what is known as the Peléean type of eruption. Anderson and Flett have given a particulary vivid account of an eruption of Mount Pelée on July 9, 1902, which they witnessed.

In this type of eruption premonitory earthquakes may occur. After these, steam, accompanied by small amounts of dust and lapilli, is emitted from the crater. The lake occupying the crater of La Soufrière was raised to boiling and the lake of Pelée was discharged with accompanying masses of mud through fissures opened by earthquakes. These preliminary stages pass gradually or suddenly to the climax, when what appears to be a black cloud composed of seething red-hot gas and solid matter rises, poises on the edge of the crater,

[8] *La Montagne Pelée et ses Éruptions, loc. cit.*

[9] T. Anderson and J. S. Flett, "Report of the Eruptions of the Soufriére in St. Vincent in 1902 and on a Visit to Montagne Pelée in Martinique," Pt. 1, *Phil. Trans. Roy. Soc. London*, Ser. A, Vol. CC (1903), pp. 353–555.

[10] *Op. cit.*

and then breaks loose like an avalanche. This cloud sweeps down the side of the crater with an acceleration on the steeper slopes, but on the gentler slopes its energy is gradually spent and it slowly comes to rest. During the descent the cloud expands; and at night the bouncing mass of red-hot boulders, hot gas, and lightning flashes in the cloud produce an awe-inspiring sight. The dying stages of the eruption may be more or less drawn out. Showers of ash may occur after the dissipation of the black cloud and may be distributed over wide areas. At Pelée eruptions of these clouds continued at intervals for more than a year before complete quiescence.

The "*nuées ardentes*," or burning clouds, as Lacroix termed these fiery avalanches, are of particular interest because they leave in their wake deposits corresponding in type to the older Crater Lake pumice. The *nuée ardente* is a mass of hot gas and solid or molten rock particles at the time of emission. The fluidity of this mass which moves down the slope is apparently independent of the size of the particles; and in the case of the Valley of Ten Thousand Smokes, Fenner[11] states that it was so great that the angle of repose was equivalent to a descent of only 1,200 feet in a distance of $11\frac{1}{2}$ miles. The temperature of the cloud is high, and vegetation in its path is not only broken but burned. Lacroix[12] noted temperatures of 210° C. in material 6 km. from the source.

The mechanism of these glowing clouds is not well understood. Anderson and Flett say:[13]

> In considering this property of perfect fluidity which the black cloud possesses we must remember its origin. Within the crater it was a molten magma, in which a considerable number of small crystals floated in a liquid which contained an enormous amount of occluded steam. As it rose in the throat of the volcano the relief of pressure allowed the gases to expand, and to free themselves from the liquid in which they were held. Sooner or later the cohesion of the liquid was overcome, and from a spongy froth the mass changed to a cloud of particles, mostly solid, but perhaps in some part liquid, each surrounded on all sides by films of expanding gases and thus the mixture of the ingredients from the first was perfect. Around each grain of dust there was a film of gases ready to expand enormously when the mass reached the upper air.
>
> The amount of expansion of which these gases are capable is so great as to be almost incredible. The small black ball which we saw emerge on July 9th in a few minutes was a great black mass, which covered more than a square mile,

[11] *Ibid.*, p. 62. [12] *Op. cit.*, p. 214. [13] *Op. cit.*, p. 507.

and the white steam, which shoots upward in the air when the cloud is dead, is still actively expanding at a great rate. This leads us to wonder whether, when the cloud emerges, it may not be partly at least composed of molten droplets which when they cool and pass into the solid condition as the cloud rolls on, give out gases which till then had been physically occluded or absorbed in the liquid. The mere pressure within the crater would be almost insufficient to compress so great a volume of gas into so small a space, especially when we remember the very high temperature of the mass.

Though Anderson and Flett believe that there was no initial explosion and that gravity caused the cloud to travel, Lacroix[14] states that there was an initial explosion to cause the outbreak, and believes that the particles left the volcano in the solid state and that gravity played a minor part in determining the speed and direction of the avalanche. He has more recently[15] stated that he considers Anderson and Flett's interpretation to be based on an exceptional eruption of Pelée.

Fenner's[16] ideas about the origin of the sand flows of the Valley of Ten Thousand Smokes are much like those of Anderson and Flett about La Soufrière:

I think that initial explosions from vents situated on the floor of the valley could hardly have had much effect as directive agents in the movement, nor would gravity produce the observed results unless the material itself possessed most unusual properties.

I would, therefore, stress the remarkable character imparted to the gas and dust mixture by a continuous evolution of gas, which must not only have eliminated almost completely the contact friction of the particles, but also have tended to drive them apart somewhat forcibly and caused the mass to spread almost as freely as a true liquid.

Concerning the explosive nature of the magma Fenner says:

. . . . the magma that rose in the fissures in the valley, though potentially explosive, did not explode at once when it rose to the surface, but a considerable time elapsed before the shift of internal chemical equilibrium had progressed so far as to lead to the climax. It is not thought that a similar course is often followed in explosive eruptions.

It is interesting to read the accounts of the phenomena at Pelée and La Soufrière with this conception in mind. Although the conditions that

[14] *Ibid.*, p. 352.

[15] "Remarques sur les matériaux de projection des volcans et sur la genèse des roches pyroclastiques qu'ils constituent," *Jubilee Vol., Soc. Géol. France*, Vol. II (1930), p. 460.

[16] *Op. cit.*, p. 72.

favored a preservation of events in the Katmai eruptions were not present in the others, we know at least that after the magma had risen into the craters at Pelée and Soufrière and when there seemed to be no physical obstacle to immediate explosion a period of gradually increasing violence intervened before the climax came. Moreover, the explosive discharge, once started did not continue until the magma was exhausted, but successively lower layers when relieved of their superincumbent load by the ejection of material higher in the conduit, experienced in turn a period of relative quietude, followed by increasing activity, and finally by explosive ejection.

The recognition of material left by pre-historic *nuées ardentes* as such must depend largely on the character of the ejecta. Lacroix[17] has furnished an excellent description of this material:

> The solid materials of the *nuées ardentes* are composed, as are those of the vertically projected types, of a mixture of cinders, lapilli, and of blocks; but they are not as are the latter classified by order of size according to the distance from the crater; blocks of several hundred cubic meters occur to distances up to six kilometers from the point of origin mixed with fine cinders, while those blocks which are projected vertically and whose dimensions are always much less, rarely occur more than 2 kilometers from the crater.
>
> Further, during the course of my observations I have never found in the material of the *nuées ardentes* fragments torn from the old crater walls, which, however, were not rare in the vertically projected material.

Lacroix then described the material of which some of these *nuées ardentes* are formed, and says:

> . . . . the vitreous types and in particular the pumice were formed of material emitted from depth at the time of explosion. The particles are angular or possibly subangular and in the case of the glassy types, angular with sharp ridges. There are few structural variations among the lapilli of a single *nuée:* they are strictly related to the large blocks which accompany them. If one studies them further and examines them under the microscope, one finds that they also are identical with the coarsest material; it thus results that in the case of *nuées ardentes* formed of pumice blocks the fine cinders are pumice, while in the case where they carry glassy andesite blocks, the cinders are formed exclusively of nonvesicular rock débris. . . . .
>
> I thus consider the blocks, lapilli, and cinders as formed of the same broken rock and differing among themselves only in dimensions.

In a more recent article[18] Lacroix has summarized the characteristics of the different types of pyroclastics by origin, and stresses the great size range of the particles, as well as the uniformity of material, as the petrologic characteristics of this type of pyroclastic.

[17] *La Montagne Pelée et ses Éruptions, loc. cit.*, p. 206.

[18] "Remarques sur les matériaux de projection, etc.," *loc. cit.*

Deposits of *nuées ardentes* easily may be separated from those of normally projected types by the lack of sorting, and also by the persistence of material to sharp boundaries. Separation from material of volcanic avalanches and similar breccias depends largely on distribution. Volcanic avalanches can travel only on the steeper slopes of the volcano; and consequently, if the deposits occur at considerable distance from the flanks, they must be of different origin. Separation of *nuée ardente* material from that of mudflows is more difficult at first sight, especially so because mudflows caused by the discharge of crater lakes may precede the eruptions, and may also occur during a series of them by the action of torrential rains upon material deposited.

As has been shown by Lacroix,[19] mudflows have great erosive powers; whereas *nuées ardentes*, though capable of flattening obstacles such as forests and habitations in their paths, do not erode. Consequently both composition and distribution of the deposits are different. Because of the erosive power of the mudflow, extraneous material such as blocks of older lava, soil, etc., are common, but are lacking in the deposits from *nuées*. Mudflow material invariably shows bedding at one place or another, but this is lacking in the material laid down dry by the *nuée ardente*.[20] Mud containing water as a diluent is necessarily of low temperature, though material from *nuées ardentes* may range in temperature to red heat, and cooled material may contain such evidences of heat as carbonized wood. Deposits from mudflows are found only in places where the flow is retarded sufficiently to drop the material carried, but *nuées ardentes* leave deposits the length of their courses and on the crater sides and on ridges, as well as in the lower valleys and plains. Mudflows are confined to valleys, whereas *nuées ardentes* may cross ridges (Lacroix),[21] thus giving a distribution inexplicable by mudflows.

To sum up, the characteristics of deposits left by *nuées ardentes* are:

1. Unsorted nature of material and lack of relation of coarseness to position of source.

2. Lack of bedding of any sort or of any alinement of particles.

[19] *La Montagne Pelée et ses Éruptions, loc. cit.*, pp. 375–82, 452–63.

[20] *Ibid.*, p. 381. [21] *Ibid.*, p. 209.

3. Material derived from one magma and no extraneous material, with the exception of carbonized vegetable remains.

4. Distribution of material on ridges and slopes as well as valleys and flats.

5. Extent greater than that of volcanic avalanches.

6. Restriction of material to sharply bounded area which is smaller than would correspond to particle size in projected type of material.

The use of these characteristics as criteria in the field involves the examination of many outcrops. No. 2 is, of course, a negative criterion; and carbonized wood as an evidence of high temperature is considered too uncertain to be included in this list.

ORIGIN OF OLDER PUMICE OF CRATER LAKE REGION

The older pumice of the Crater Lake region duplicates the characteristics of *nuées ardentes* discussed and is therefore tentatively ascribed to such an origin. The deposit is considered to be formed, not from one, but from a series of eruptions. Further detailed study of the distribution and other features would undoubtedly furnish additional data to illustrate these characteristics more fully. It is believed, however, that the available evidence justifies the assignment made.

OTHER DEPOSITS OF NUÉES ARDENTES

Few attempts have been made to explain heterogeneously sorted pyroclastic material as deposits of *nuées ardentes*. A notable exception to this is the paper by Völzing[22] on the trass deposits of the Brohl Valley, and the paper by Fenner.[23] Lacroix mentions the recognition of similar deposits in Sumatra[24] and states that the *lahars*, or mudflows of Java, differ from Peléean eruptions only in that the discharge of the crater lake is more serious than the succeeding *nuées ardentes* of which he has found evidence. Undoubtedly deposits of other *nuées ardentes* exist. It should surely be possible in many instances to separate such deposits from those of mudflows,

[22] K. Völzing, *Der Trass des Brohltales* (J. B. Konig. Preuss. Geol. Landes, Band XXVIII [1907] (1910), pp. 1–56.

[23] *Op. cit.*, p. 23.

[24] "Remarques sur les matériaux de projection, etc.," *op. cit.*, p. 465.

and care should be exercised in the field to prevent confusion between the products of these two dissimilar processes.

COMPARATIVE SIZE OF THE CRATER LAKE ERUPTIONS

Though much material has been washed from the area adjacent to Crater Lake, sufficient remains to show that the older pumice contained at least $8\frac{1}{2}$ cubic miles of material and the younger pumice at least $2\frac{1}{2}$ cubic miles. The distance traveled by the *nuées ardentes* and the amounts of material carried by them indicate that they were of tremendous size and force. Whereas those of Pelée traveled 6 kilometers to the sea and those of the Valley of Ten Thousand Smokes $11\frac{1}{2}$ miles to the sea, these of Mount Mazama traveled 23–36 miles, carrying great masses of pumice boulders the whole distance. The succeeding eruption that furnished the granular pumice hurled granules as much as an inch in diameter to distances of 80 miles and may have furnished the volcanic dust which settled in Baker and Wallowa counties and is there seen interbedded with the Recent alluvium.

CONTACT PHENOMENA ASSOCIATED WITH THE CASSIA BATHOLITH, IDAHO[1]

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ABSTRACT

The intrusion of the Cassia batholith in Idaho was accompanied by clearly defined contact phenomena expressed by the impregnation of "igneous" material into quartzite, and in such a manner as to make it resemble granitic rock. While the magma crystallized as granodiorite, it sent forth emanations into the invaded rock and by progressive replacements produced therein a broad zone of porphyritic granite. As a result of the progressive granitization of the quartzites in the contact zone, the batholith is now about three times as large as it would have been had "replacement" not been a factor in its intrusion.

It is altogether likely that the changes noted in the contact zone of the Cassia batholith may also be expressed in the crystalline schists in extensive metamorphic regions. The replacement origin of the microcline phenocrysts in the hybrid porphyritic granite also directs attention to the probability that the microcline phenocrysts in normal granitic rocks also may have been formed late by replacement.

INTRODUCTION

Associated with the Cassia batholith in Cassia County, Idaho, is a broad marginal zone of hybrid rock which is partly igneous and partly sedimentary in character, but so much like igneous rock in mineral composition that it must be regarded as an essential part of the batholith and is included within its mapped limits. It is transitional between the massive granitic rock of the interior of the batholith and the quartzites of the invaded strata. Detailed examination of the marginal zone shows progressive granitization of the quartzites, apparently by magmatic emanations from the invading batholith. By this process of granitization the batholith has grown beyond the limits of the strictly magma facies, and its exposed portion is nearly three times as great as it would have been if impregnation of the quartzite by granitic material had not played a part.

Unusual features[2] of the batholith were observed when the region

[1] Published by permission of the Director, U.S. Geological Survey, and the Director, Idaho Bureau of Mines and Geology. The writer wishes to express his gratitude to Messrs. G. F. Loughlin, C. S. Ross, C. P. Ross, A. H. Koschmann, and others who have so kindly made suggestions in the preparation of the paper.

[2] A. L. Anderson, "Geology and Mineral Resources of Eastern Cassia County, Idaho," *Idaho Bur. Mines and Geol. Bull.* XIV (1931), pp. 49–59.

was visited in 1930, but not until specimens from different parts of the batholith were examined microscopically did the abnormal textural and compositional characters become strikingly apparent. These features prompted the writer to revisit the batholith in September, 1932, and to undertake systematic detailed studies across the body. This paper has largely evolved from the later studies, for it was then learned that much of the exposed part of the batholith is composed of a "replacement" granite produced within the contact zone.

The Cassia batholith forms the core of the southern part of the Albion Range in Cassia County, beginning near the Utah line and extending northward for about 16 miles (Fig. 1). It also appears in the eastward-facing scarp of South Mountain, the young tilted block mountain, about 2 miles west of the southern end of the Albion Range. Areal exposures of the batholithic rock, including the smaller outliers, cover about 60 square miles. The batholith has been deeply eroded and forms the highest as well as the lowest part of the Albion Range, a vertical distance of about 5,000 feet. High walls capped by the more resistant sedimentary strata (Fig. 2) locally furnished exceptionally good exposures.

Detailed studies were made across the contact zone on lower Green Creek near the northeast end of the batholith (Fig. 2) and also across the batholith about 10 miles to the southwest through the heart of the Cassia City of Rocks. More widely scattered specimens of rock were collected from other parts of the batholith and its outliers both in the Albion Range and in nearby South Mountain.

INVADED ROCK

The strata invaded by the Cassia batholith are quartzites in the lower part of the pre-Cambrian Albion Range group, here substituted for Harrison series,[3] which is preoccupied. This group continues southward into the Raft River Range of northwestern Utah[4] and resembles a series of pre-Cambrian rocks in the Wasatch Range, which Blackwelder[5] has shown to underlie sandstones, conglomer-

[3] *Ibid.*, pp. 24–29.

[4] B. S. Butler, G. F. Loughlin, and V. C. Heikes, "The Ore Deposits of Utah," *U.S. Geol. Surv. Prof. Paper 111* (1920), p. 78 and map.

[5] Eliot Blackwelder, "Wasatch Mountains Revisited," *Abst. Bull. Geol. Soc. Amer.*, Vol. XXXVI (1925), pp. 132–33.

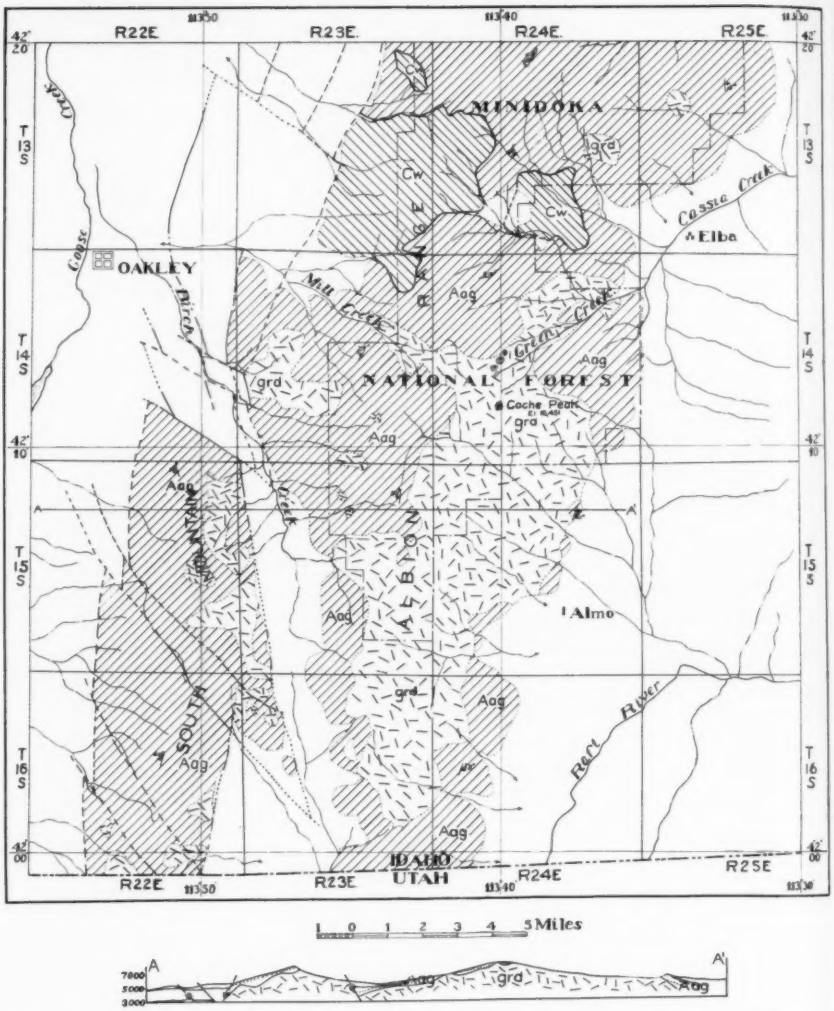

FIG. 1.—Map showing location of the Cassia batholith and its outliers in the Albion Range and South Mountain. The intrusive rock is marked *grd* and includes the contact zone. It invades the quartzitic strata of the Albion Range group (*Aag*) and is in part capped by Tertiary lavas and Quaternary alluvium (undifferentiated and left blank). The Wells formation, of Pennsylvania age, is marked *Cw*; the faults by heavy lines.

ates, and slates of late Algonkian age. The writer considers the Albion Range group to be of pre-Beltian age,[6] because of this resemblance and the high degree of regional metamorphism. The group consists mainly of metaquartzites with some intercalated marbles and schist in its middle and upper parts. The lower part, which is the only part of special interest in this study, is more than 4,000 feet thick and consists mainly of medium- to fine-grained, pure

FIG. 2.—Marginal zone of the batholith on lower Green Creek near the north end of the batholith. Darker color of the upper transition zone and its relict sedimentary structures may be plainly seen. There is a sharp contact between this zone and the white quartzites above, and a gradational one with the more massive porphyritic granite below. The rock shows its hybrid character microscopically throughout the 600 feet of the exposure.

quartzite, completely recrystallized by dynamo-metamorphism. This quartzite contains a few slightly micaceous beds, and one bed of conglomerate the pebbles of which have been so extremely squeezed and recrystallized that it now forms a conglomerate gneiss.

The strata have been arched into a broad dome or anticline in the Albion Range dipping outward on both flanks of the range, as illustrated in the cross section of Figure 1. They also dip away from the

[6] *Op. cit.*, pp. 27–29.

walls of the batholith. Elsewhere in the Albion Range, and also in the Raft River Range in Utah, the group rest on Paleozoic strata (Carboniferous in the Albion Range), having been brought into this position by great, low-angle overthrusts. A thin shell of the strata dips down the west slope of South Mountain.

INVADING ROCK

MAJOR STRUCTURAL FEATURES

Contact between the quartzite and the transitional border zone of the batholith is fairly sharp and is commonly less than 100 feet wide (Fig. 2). There is not much doubt as to where the igneous or magmatic effects have ceased and the unaltered quartzite begins. Sedimentary structures are preserved in many places for some distance within the contact zone (Fig. 2), but the rock within this zone is of distinctly darker color than the white quartzite above it. It is the contact between the transition or hybrid zone and the quartzite that has been taken as the boundary of the batholith as the rock of the hybrid zone grades imperceptibly into undoubted igneous rock that forms the interior of the batholith. The inner limit of the hybrid rock must be largely determined microscopically.

The Cassia batholith has most of the characteristic features usually ascribed to batholiths. It forms a plutonic mass exceeding 40 square miles in surface area, and is in general dome-shaped, with minor cupola-like irregularities which appear as outlying or satellitic stocks but are doubtless continuous with the main body beneath a thin quartzite capping. Had erosion continued everywhere to an additional depth of 500 feet, the granitic rock now exposed at the surface probably would have been about doubled. The boundaries of the granitic rock dip rather steeply and the body grows larger with depth. The eastern wall of the batholith, as exposed in the Albion Range, plunges eastward with a dip of about 45°, which exceeds the dip of the invaded strata. Its western wall plunges less steeply, apparently not much more than 15° or 20°, and faulting has brought it to view again in South Mountain. The batholith shows no apparent bottom, and, although it has been eroded to a depth exceeding 5,000 feet, the character of the rock gives no indication of an approaching floor. The body is probably continuous at depth with the granitic mass in the core of the Raft River Range.

TEXTURE AND COMPOSITION

The batholith exhibits some extraordinary variations in texture and composition. Its inner part is composed of a light-gray to nearly white equi-granular rock of medium-to-coarse grain with the prevailing composition of granodiorite, although certain parts are somewhat more alkalic. The rock maintains essentially its same coarseness of grain into the marginal zone, but there scattered phenocrysts appear and the rock assumes a faint, gneissic banding, which becomes more pronounced in the outermost parts of the zone. With the change in texture there is also a change in composition and the rock becomes a porphyritic granite. The porphyritic and gneissic zone is also marked by a somewhat darker color than the inner part and by striking microscopic differences to be described in the following pages. Its outer portion in particular retains relict bedding structures (Fig. 2) that have apparently been inherited from the invaded quartzites. The very margin is usually a zone from 50 to 100 feet wide of even darker-colored rock with pronounced banded and in part schistose structure, which is decidedly hybrid in character, showing distinctly sedimentary as well as igneous features.

Porphyritic granite constitutes about two-thirds of the exposed area of the batholith, including all the exposures in South Mountain and in the outlying stocks, and more than half of the main body in the Albion Range. It extends deep into the batholith, for it prevails from the top to the bottom of the South Mountain scarp, a vertical distance of about 1,800 feet. It also forms the rock of the highest part of the Albion Range and extends inward from the margins for several thousands of feet, especially from its eastern wall. The granodiorite facies is mainly confined to the Cassia City of Rocks area, a mile or more within the quartzite border, and covers about 22 square miles.

PETROGRAPHY

Granodiorite.—The typical granodioritic facies consists of rather uniform and well-formed grains and only rarely exhibits a porphyritic tendency. A typical specimen was found to have zoned andesine (53 per cent), quartz (25 per cent), microcline (12 per cent), and biotite (7 per cent), and as accessory minerals, not estimated in the total, zircon, apatite, titanite, and magnetite, and with muscovite, epidote, and zoisite as secondary minerals. Other specimens show

garnet and rutile, as well as secondary chlorite. The proportions of the essential minerals differ somewhat in other specimens, and in some the microcline content is nearly equal to that of the plagioclase, but for the most part the prevailing composition is that of granodiorite.

The plagioclase is distinctly zoned and has interiors as calcic as andesine (Ab_{64} An_{36}) and exteriors as alkalic as oligoclase ($Ag_{78}An_{22}$). In some of the sections the zoned crystals have broad, clear rims of oligoclase ($Ab_{78}An_{22}$) that are apparently later additions to the more calcic core. All plagioclase grains are well formed, and show clearly defined, polysynthetic twinning, in part combined with Carlsbad twinning. The biotite apparently crystallized after the plagioclase, for it forms grains between the plagioclase crystals and even sends protuberances into the plagioclase as though replacing it. Quartz followed after biotite and has its usual interstitial relations to the biotite and plagioclase. Microcline, however, was one of the last minerals to complete its growth and much of it is late and apparently deuteric. Its larger grains penetrate the other minerals irregularly and in addition hold rounded and irregularly corroded quartz and plagioclase grains (Fig. 3). It is therefore like the microcline described by Gillson[7] and the writer[8] in the Pend Oreille district in northern Idaho where the microcline is a late-stage mineral and mostly introduced after the rock had solidified. It is the irregular distribution of this late mineral in the interior core of the batholith that causes slight variations in its granodioritic composition. Excellent myrmekite structures have been induced in some of the plagioclase grains in contact with microcline. Titanite is also a late-stage mineral, likewise most of the magnetite, both of which have relationships suggesting a deuteric origin. Garnet is developed locally. Other late changes are also manifested. Some of the biotite has been altered to a reddish-brown, subtranslucent substance, and also partly altered to epidote and chlorite. Some of the plagioclase also shows partial alteration to epidote. Secondary white mica, in part as large flakes

[7] J. L. Gillson, "Granodiorites of the Pend Oreille District of Northern Idaho," *Jour. Geol.*, Vol. XXXV (1927), pp. 1–20.

[8] "Geology and Ore Deposits of the Clark Fork District, Idaho," *Idaho Bur. Mines and Geol. Bull.* XII (1930), pp. 29–32.

of muscovite, is abundant in some parts of the granodiorite body. It is commonly developed in the plagioclase and rarely in the microcline. In general the feldspars are relatively clear when compared with the feldspars in other rocks of the batholith. Late-stage

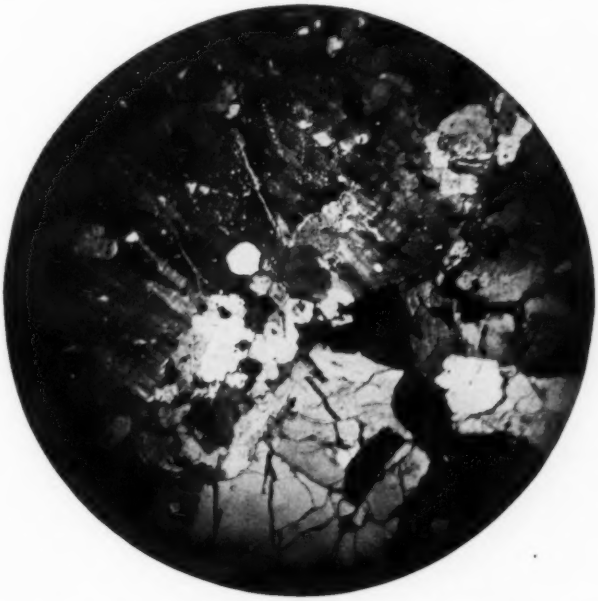

FIG. 3.—Photomicrograph of the granodiorite with late stage microcline replacing the earlier quartz and andesine grains. Phenocrysts of microcline in the granodiorite core of the Cassia batholith are not common but where present their relations are the same as in the porphyritic granite and they are the product of the emanations escaping from the magma through already crystallized rock of the intrusive core. ×16.

changes have affected all the interior granodiorite core to some extent, but only parts of it to marked degree.

Porphyritic granite.—A minor part of the porphyritic granite zone may represent the normal intrusive core thoroughly impregnated by late-stage microcline of phenocrystic size, but the greater part, and especially that with darker color and traces of gneissic banding, has an entirely different texture and different composition.

Its microscopic texture is strikingly different from that of the granodiorite, for all the porphyritic and gneissic facies contain streaks, lenses, or irregularly shaped masses of interlocking quartz grains (Figs. 4 and 5) with parallel-oriented crystals of biotite. These mosaics or patches of interlocking quartz grains are scattered near

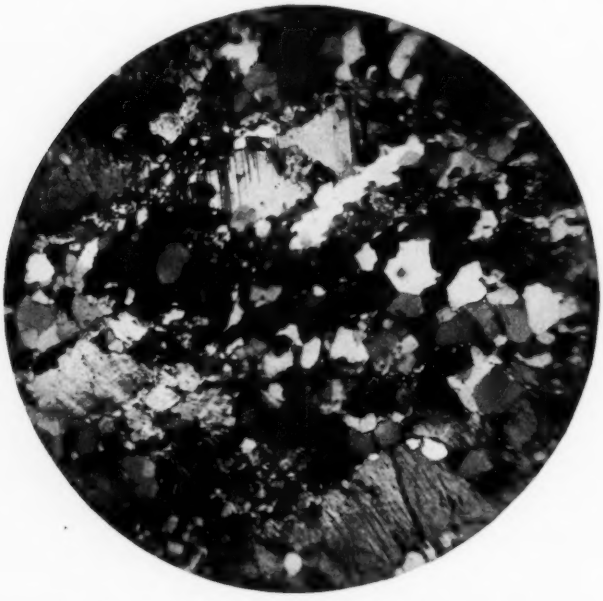

FIG. 4.—Photomicrograph showing patches of biotite-bearing quartzite remaining in the porphyritic granite 600 feet below the upper contact on Green Creek. This specimen was from slightly gneissic porphyritic granite at creek level. It shows some albite and much microcline in addition to the quartzite remnant. ×16.

the granodiorite core, but they become increasingly abundant near the outer margin and eventually unite to form the invaded quartzite. They are remnants of the invaded quartzite and are in undisturbed position. It is these quartzite clusters that modify what otherwise would appear as a typical igneous texture. The quartz mosaics are generally not readily distinguishable, with the exception of thin section, because of the preponderance of the invading min-

erals, but they cause a peculiar lack of mineral definition in the hand specimen and a lack of sharpness in the texture of the usual porphyritic granular rock. The rock is, however, decidedly igneous in appearance and was so regarded by the writer before microscopic studies were made.

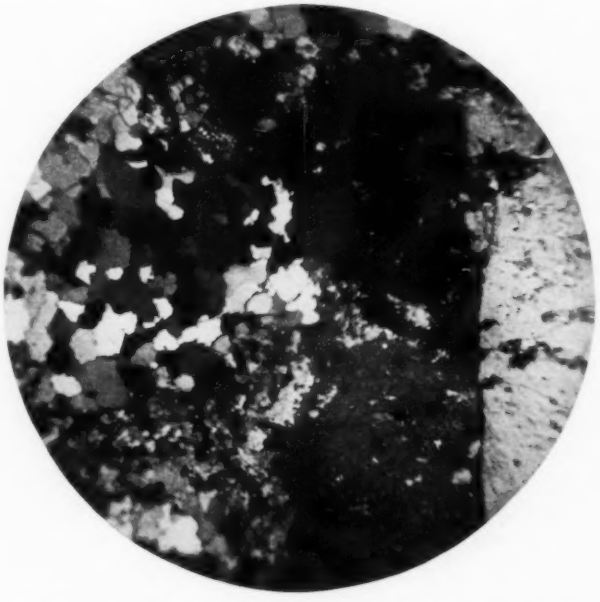

FIG. 5.—Photomicrograph showing granular quartz mosaic in the porphyritic granite west of Almo near the Cassia City of Rocks. This specimen was collected nearly a mile in a horizontal distance from the margin of the batholith. Rock with similar porphyritic texture and slightly gneissic structure continues inward for at least another half-mile. The irregular border of the microcline phenocryst that partly replaces the quartz mosaic is plainly shown, as is the marked tendency for the phenocryst to develop idiomorphic outlines. ×16.

The most notable megascopic feature of the rock is the size of the microcline phenocrysts, which are from $\frac{1}{2}$ to 2 inches and exceptionally as much as 6 inches long and are scattered sporadically and without definite orientation, thereby cutting the cleavage of the rock at any angle whether the banding be extremely faint or pronounced.

These show rather well-defined outlines (Fig. 5) and are embedded in a granular matrix of medium-to-coarse grain of much the same size as the minerals composing the granodiorite.

Minerals of the porphyritic granite, in addition to the microcline, the quartz mosaics, and biotite, are albite ($Ab_{94}An_6$), titanite, zircon, magnetite, apatite, garnet, muscovite, epidote, chlorite, and zoisite. Of the entire group, the microcline is by far the most abundant. The groups of interlocking quartz crystals show strain extinction and enclose parallel flakes of biotite, thus presenting the same textural features as the biotite-bearing quartzite at the very border of the batholith. The biotite occurs only in the quartz mosaics and thus differs from the biotite in the granodiorite core where it is interlocked with the other minerals. In some sections, however, the biotite occurs sparingly as partly replaced flakes in the feldspars. The biotite is apparently a result of the general contact phenomena, for it does not extend beyond the contact zone.

The plagioclase is unusually interesting both because it lacks the zoning so characteristic of the plagioclase of the granodiorite and because of its highly sodic character ($Ab_{94}An_6$). It has the usual pronounced polysynthetic twinning (Fig. 6), with the exception of where this twinning has been partly masked by secondary products (Fig. 7). Its crystals are generally well shaped and of about the same size as the more calcic ones in the granodiorite. They are, however, not nearly so abundant and are very subordinate to the microcline. The albite is more or less uniformly distributed throughout the porphyritic zone and a decrease is invariably accompanied by an increase in microcline. The albite is obviously a replacement of quartzite, for not only does it hold partly assimilated quartz grains within it, but it also advances more or less irregularly into the remaining quartz mosaics, replacing both the quartz and its contained biotite (Figs. 6 and 7).

Microcline occurs in sizes from those of small grains in the groundmass to the large phenocrysts, and it all shows distinct replacement of the albite and biotite-bearing quartzite (Fig. 8). Much of the microcline is full of partly assimilated quartz and plagioclase, part of which occur as rounded and corroded grains and part as almost skeleton-like forms (Fig. 8). Some of the microcline crystals

retain distinct shadows of the former quartzite and plagioclase grains. The borders of the microcline are usually minutely uneven as the mineral penetrates irregularly into the adjacent grains, but if viewed less closely the crystals display rather marked idiomorphism (Fig. 5), for they tend to assume their own crystal form during

FIG. 6.—Photomicrograph showing a large crystal of albite replacing quartzitic matrix about 400 feet within the contact zone. ×16.

the replacement. The relations here expressed are like those described by the writer[9] in the porphyritic granodiorite in the Cabinet Mountains in northern Idaho adjacent to the Pend Oreille district where the large microcline phenocrysts were the last to form and have done so by replacing the earlier plagioclase and quartz of the normal granodiorite. Not all the microcline phenocrysts show characteristic twinning or grating structure throughout; in many crystals the plaid effect appears only in patches, but extinction angles on

[9] *Ibid.*, pp. 29–32.

cleavages prove that the remaining untwinned part is microcline and not orthoclase.

Titanite is more abundant than in the granodiorite and gives evidence of late or deuteric introduction. A few microscopic garnets are present. Zircon and magnetite are more plentiful than in the granodiorite.

FIG. 7.—Photomicrograph showing albite crystals replacing quartzite in the upper part of the contact zone. Some rounded quartz grains are retained in the plagioclase crystals. The twinning of the albite is in part obscured by abundant secondary white mica. ×16.

Epidote and chlorite show the same relations as in the granodiorite and are more abundant than in the intrusive core. Among the secondary minerals, however, white mica, or muscovite, is especially abundant and much of the albite has been converted into coarse, muscovite aggregates through which the polysynthetic twinning is only faintly visible. In some places the muscovitization has extend-

ed into the quartz as well. It has, however, affected the microcline but very little, and perfectly clear microcline crystals may lie along or surround albite that has been almost wholly changed to aggregates of coarse mica. The excessive alteration in the porphyritic zone thus stands in marked contrast to the less feeble muscovitization of the granodiorites; in short, the porphyritic granite reveals progres-

FIG. 8.—Photomicrograph showing partly replaced albite crystal and a small quartzite remnant in a large microcline phenocryst. Shadows or small remnants of other grains are numerous in the phenocryst. ×36.

sive granitization of the quartzite, an impregnation in successive stages by biotite, albite, microcline, titanite, and other accessories, and finally extensive sericitization or muscovitization.

Schistose border rock.—The schistose border differs from the rock already described mainly in that it is more highly banded and schistose, retains the jointing and preserves the bedding of the quartzite, has a somewhat darker color because of increased biotite content.

and expresses its hybrid character megascopically. The minerals in this zone are the same as those in the porphyritic granite, and their relations are similar, but their proportions are much more variable. Part of the rock in this zone is porphyritic, but microcline is not nearly so uniformly distributed as it is farther in, and in many places is not nearly so abundant. Its place is taken by more albite and by more numerous and larger patches of the biotite-bearing quartz mosaics. Secondary muscovitization has also been much more erratic, intense in some places and absent in others, especially near the contact. In some places, however, this action has extended into the quartzite a short distance beyond the marked contact zone.

SUMMARY AND CONCLUSIONS

The Cassia batholith exhibits clearly defined contact phenomena expressed by the impregnation of "igneous" material into quartzite and in such a manner as to tend to make it resemble granitic rock. In the course of intrusion the granodiorite sent forth emanations which made progressive changes in the contact zone while the intrusive magma itself crystallized in the normal manner. These emanations first caused widespread formation of biotite in the quartzite and then, as the solutions became sodic, extensive albitization of the biotite-bearing quartzite. As the emanations continued to stream through the wide border or contact zone, they apparently became increasingly enriched in potash as a result of which large crystals of microcline were deposited by replacement throughout most of the contact zone and produced a granitic rock with marked porphyritic texture. Late during this stage the emanations caused the formation of titanite, garnet, magnetite, and probably zircon and apatite. Still later some epidotization and chloritization took place, but the most conspicuous process was muscovitization of albite and quartz, and to a slight degree of the microcline. These contact effects were extensive and produced the porphyritic and gneissic rock of igneous appearance that constitutes about two-thirds of the exposed part of the batholith. The emanations also permeated the granitic core itself to some degree and produced therein some late changes similar to those in the contact zone.

Somewhat similar "replacement" granites have been observed by

Sederholm,[10] Quirke and Collins,[11] Adams and Barlow,[12] Fenner,[13] and La Croix,[14] all of whom have attributed many changes in the invaded rock to magmatic emanations even to the extent of forming granite. Late changes in the intrusive rocks themselves have been ascribed by Gillson to the action of emanations.[15] There is, therefore, growing recognition of this kind of contact metamorphism or granitization which is so well expressed in the Cassia batholith. Similar effects or contact granites also have been noted by the writer about portions of the Idaho batholith and are now under investigation.

It is altogether likely that the changes noted in the contact zone of the Cassia batholith also may be expressed in the crystalline schists, especially the quartz biotite-plagioclase schists, in extensive metamorphic regions. The possibility that the plagioclase and biotite, and perhaps part of the quartz, have been introduced by magmas should be carefully weighed in detailed study of metamorphic areas. Microcline in schists near intrusive granitic bodies is very likely the result of impregnations of the kind expressed in the contact zone of the Cassia batholith. The contact phenomena associated with the Cassia batholith are possibly exceptional only in the degree to which the affected rock has become more "igneous" than "metamorphic" in appearance.

The contact zone of the Cassia batholith also directs attention to the replacement origin of microcline phenocrysts. Microcline phenocrysts are by no means confined to contact zones alone but commonly

[10] J. J. Sederholm, "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland," *Bull. de la Commission Géologique de Finland*, No. LVIII (1923), pp. 58, 128–38.

[11] T. T. Quirke and W. H. Collins, "The Disappearance of the Huronian," *Geol. Surv. Can. Mem. 160* (1930).

[12] F. D. Adams and A. E. Barlow, "The Geology of the Haliburton and Bancroft Areas, Ontario," *ibid., Mem. 6* (1910), pp. 81–83, 179–80.

[13] C. N. Fenner, "A Mode of Formation of Certain Gneisses in the Highlands of New Jersey," *Jour. Geol.*, Vol. XXII (1914), pp. 697–702.

[14] La Croix, "Le granit des Pyrénées et ses phénomènes de contact," *Carte géol. de France*, No. XXI (1910), p. 26.

[15] J. L. Gillson, "Granodiorites of the Pend Oreille District of Northern Idaho," *Jour. Geol.*, Vol. XXXV (1927), pp. 1–20, and "Petrography of the Pioche District, Lincoln County, Nevada," *U.S. Geol. Surv. Prof. Paper 158d* (1929), pp. 77–86.

occur as phenocrysts in the porphyritic granitic rocks. The writer[16] has already described them in the porphyritic granodiorites of northern Idaho where they are the latest mineral to form and reflect processes like those expressed in the Cassia batholith, but where the potash-rich emanations soaked through the body of the granodiorite itself during or shortly after crystallization. Later studies of the porphyritic zones in parts of the Idaho batholith as well as in parts of the Nelson batholith in northern Idaho and Southern British Columbia have confirmed the late age and replacement origin of the microcline phenocrysts. Spurr and Garrey[17] were probably first to suggest that microcline phenocrysts may form after the solidification of the magma and by recrystallization through solutions, but the idea has not gained prominence, and, so far as can be learned, nothing further in this line has been published until now.

[16] *Op. cit.*, pp. 29–32.

[17] J. E. Spurr and G. H. Garrey, "Economic Geology of the Georgetown Quadrangle, Colorado," *U.S. Geol. Surv. Prof. Paper 63* (1908), pp. 93–95.

THE LOON LAKE PLUTON, BANCROFT AREA, ONTARIO, CANADA

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Johns Hopkins University

ABSTRACT

The Loon Lake batholith, which is supposed to be part of larger granitic masses underlying the Canadian Shield, was found to be a small, funnel-shaped intrusion. Its structure and shape is in complete accordance with the structure of the surrounding sediments and metamorphics.

INTRODUCTION

The Loon Lake pluton[1] is situated a few miles south of the center of the Bancroft map accompanying the report by Adams and Barlow of the Canadian Geological Survey. In that report reference is made to "the South Bay granite batholith in the township of Chandos."[2]

During a short visit in Canada the writer had occasion to visit this region and to investigate the particular situation of the previously mentioned granite intrusion.

AREA AND PROBLEMS

The pluton itself is small, approximately 3×5 miles, and is therefore probably not the most typical representative of its kind in that region. Barlow and Adams have recognized in their excellent report that the boundaries of the pluton dip *under* the granite, similar to the boundaries of the Methuen batholith farther south and southeast. They believe that the sediments have "sagged" into the upwelling batholith. The Loon Lake and Methuen batholiths would then be the highest portions of large, underlying granite masses.

The question arises whether the whole area is underlain by granites, which erosion has only partly reached, or whether the granitic

[1] The term "batholith" is avoided intentionally because it does not fit the situation Concerning the use of the term "pluton," see Hans Cloos, *Zur Terminologie der Plutone*, Fennia 50 (Helsingfors, 1928).

[2] F. D. Adams and A. E. Barlow, "Geology of the Haliburton and Bancroft Areas, Province of Ontario," *Can. Mem. No. 6* (1910).

areas are smaller intrusive bodies, partly stocks, lopoliths, or even sills within a series of metamorphics. In other words, do the granites of the region *underlie* the sediments of the Canadian Shield? Are they intruded *into* or *between* the sediments? Do they lie *above* and *between* them, penetrating the sediments along narrow channels which widen upward? Furthermore, is the region exposed at a low level, showing the roots of batholithic intrusions? Do we see their uppermost portions?

The solutions of such large problems cannot be found in the small area which the writer examined, or during a short visit; but some important and pertinent evidence can be found in this region. It is the purpose of this paper to call attention to the possibilities and problems and to indicate one means of solution.

THE ROCKS OF THE REGION

The report mentioned describes the rocks fully and very comprehensively. A number of granite bodies seem to penetrate a roof of sediments and earlier intrusives. The wall rocks consist of ortho- and para-gneisses, amphibolites, gabbros, diorites, limestones, and dolomites. The granite itself is medium to coarse grained and reddish or gray. Innumerable inclusions occur in the granite.

STRUCTURE AND STRUCTURAL ELEMENTS

The granites are foliated throughout the region visited. The foliation is due to magma movements, according to Barlow and Adams, who described the feature carefully.

A number of additional structural elements were found by the writer which are of great value in determining the direction of magma movements and permit conclusions to be reached concerning the mode of emplacement of the granite.

The structural elements are as follows:

1. A very distinct foliation (already mentioned).[3]

2. Inclusions, arranged with their major axes parallel to each other and to the foliation planes of the granite. These inclusions consist largely of amphibolite and other fragments which were torn loose from the walls, roofs, and maybe floors of the pluton. They

[3] *Ibid.*, pp. 11, 17, 51, 52, etc.

are all oriented and do not lie scattered within the granite without strict relation to the granitic foliation and the granitic contacts. The orientation of the inclusions is closely related and dependent upon the magma movements in which the inclusions took part passively.

3. A very distinct, linear arrangement of minerals, mineral patches, and spindle-shaped inclusions indicates flow lines. This arrangement can be seen in practically all foliation planes. Occasionally, if the foliation is absent or weak, the granite seems structureless in horizontal surfaces; but vertical or steeply inclined surfaces show the linear arrangement. This is specially true within the region which is mapped as "massive" by Barlow and Adams.

4. Schlieren occur frequently and were already mentioned by the former authors. The schlieren also are arranged parallel with the foliation planes and inclusions.

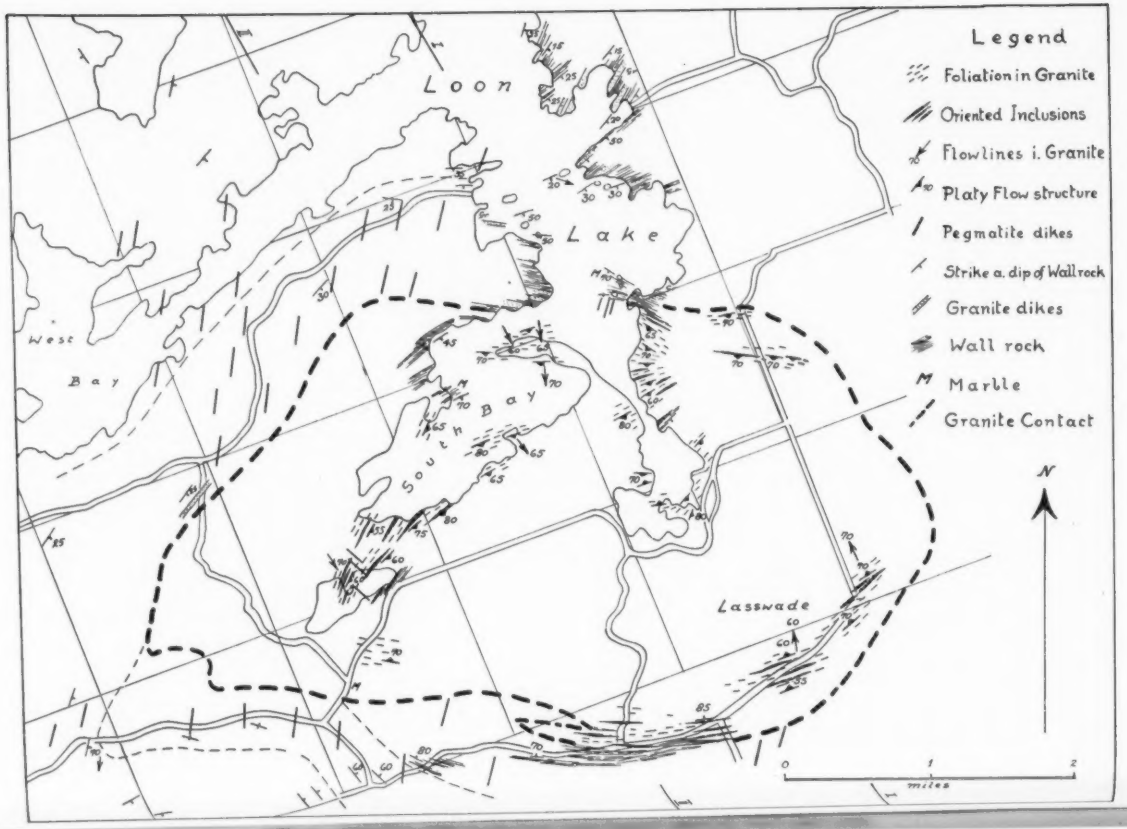
5. The joints are somewhat problematical. They can be seen throughout the region but do not seem to resemble the joints related to the flow structure as in other regions. The great number of pegmatite dikes follow a north-northeast to south-southwest trend, thus indicating a uniform direction of jointing. The pegmatite dikes dip steeply as a rule and are abundant in the surrounding wall rock and granite.

THE RELATION OF GRANITE, WALL ROCK, AND PEGMATITE DIKES

A large percentage of the visible contacts between the granite and wall rock are concordant with the pre-granitic wall-rock structure.[4] Long-continuing discordant contacts were not observed. This is well shown in the map (Fig. 1), which pictures the parallelism of wall-rock strike and contacts. Inclusions are broken loose along bedding and foliation planes, forming thin sheetlike fragments, the contacts of which are largely concordant and only on the narrow ends discordant. If a rough estimate may be permitted, perhaps not more than 10–15 per cent of all the contacts would be found to be discordant, if their lengths were measured and compared with the total contact length.

A large number of granite dikes, or largely concordant, steeply

[4] *Ibid.*, p. 11.


Loon
Lake
West
Bay
South
Bay
Lasswade
Legend
Foliation in Granite
Oriented Inclusions
Flowlines i. Granite
Platy Flow structure
Pegmatite dikes
Strike a. dip of Wall rock
Granite dikes
Wall rock
Marble
Granite Contact
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dipping sills, have penetrated the amphibolites in the northeastern portion of the Loon Lake region. The penetration of gneiss[5] with dikes creates the impression of a granite body with a number of wall-rock inclusions. On the other hand, the wall rock actually predominates. Its general strike is not dislocated, which shows that it remained in place, in contrast to the wall rock within the actual granite body where flow movements have carried the fragments away and reorientation has taken place.

The pegmatite dikes, on the other hand, are discordant. They follow largely one direction throughout the region, and their trend does not seem to be influenced by rock boundaries or rock structure.

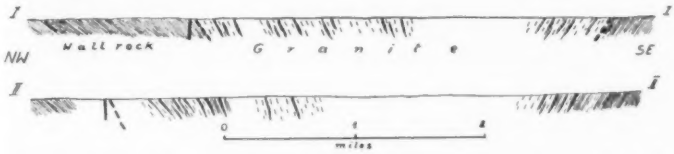

FIG. 2.—Two sections through the Loon Lake pluton, Bancroft area, Ont., Can. Horizontal equal vertical scale.

This relation between granite, wall rock, and pegmatite dikes is an interesting one. The granite was intruded concordantly for the most part. As consolidation of the entire complex continued, partly owing to granitic intrusions, the discordant dikes made their appearance, in a direction which is uniform over a large area—*regional*, so to speak. During the closing stage of consolidation joint systems were formed and filled with dike material. This relation has been found in many other batholithic intrusions; but in these, as a rule, the earliest joints opened in close relation to the flow structure. Regional joints cutting across rock boundaries and extending into the wall rock are usually of a later age.

ARRANGEMENT OF STRUCTURES

The map and sections (Figs. 1 and 2) show very clearly the arrangement of granite and wall-rock structure.

The wall-rock structure, bedding, foliation, and cleavage dip under the granite on all sides. The dip angle increases toward the gran-

[5] See Bancroft sheet.

ite from 20° to 80°, never exceeding 80°. Everywhere the platy flow structure of the granite is parallel to the wall-rock structure and to the contacts. The inward dip continues nearly to the center of the pluton. The flow lines pitch toward the center, also, being steep within the southern half of the granite. The area with vertical dip is very small.

Wall rock and internal granite structure are conformable in strike and dip as far as can be observed. As there is no exception to this rule, one might be justified in concluding that this relation continues to some depth. The dip planes of the structures, on the other hand, form a funnel, indicating downward narrowing of the pluton. How narrow it may be in depth cannot be predicted. Assuming a continuing dip downward, the pluton would narrow to a channel 2 miles by 1 mile in horizontal cross section at a depth of 3 or 4 miles.

CONCLUSIONS

The Loon Lake pluton appears to be a funnel-shaped granite body with inward-dipping contacts. The structure points toward a rather narrow conduit.

The shape of the intrusive is the original one, it is believed by the writer, and not the result of a sagging or foundering roof above a larger batholithic mass. There are no indications of stoping other than the presence of small inclusions which are split from the wall rock along its weakest planes. As all contacts are sharp, assimilation does not seem to have played an important part.

All wall rock fragments are oriented with the magma stream and not scattered at random through the granite. Sinking blocks of a foundering roof could not be oriented in such a systematic manner. Their orientation should be accidental and in any direction. Instead of disorder, strictest order and alinement into a uniform movement is found. The movement must have been considerable, or the plain and very pronounced structure could not have resulted. A downward movement of such intensity can hardly be imagined; the upward impulse is obvious. Inclusions were caught in the magma and were moved along with it in the same direction. It does not seem possible that the difference in specific gravity between consolidated wall rock and the magma could be great enough to overcome this movement,

aside from the fact that not any trace of settling or sinking wall-rock fragments is found within this upward-moving magma.

The Loon Lake pluton, as conceived by the writer, is a granite body which was intruded into a series of sediments and metamorphics, forming a succession of dikes around the margins and a mass of pure granite at the center. The number of inclusions decreases from the margins toward the center. This granite-filled funnel is not a part of a batholith underneath, but one of many openings through which the magma has reached higher levels, in close relation with the surrounding wall-rock structure, not breaking the roof but intruding between sediments and crystalline schists, and respecting structural and petrographic boundaries.

It may be of interest to call attention to the Methuen batholith a few miles farther southeast and south of Loon Lake. This granite shows a very distinct foliation, inclusions, etc. The structure lies flat (see Bancroft map), as already observed by Barlow and Adams. The wall-rock structure dips toward the granite and under it. It seems to the writer that this pluton is either a narrow body which widens upward or a shield or sill-like body, probably with a flat floor.

As not all plutonic masses of the Canadian Shield are the highest portions of bottomless batholiths, a detailed structural study would produce important results toward the solution of the problems of this region in particular and the batholith problem in general.

IGNEOUS ROCKS OF THE SHENANDOAH NATIONAL PARK AREA[1]

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ABSTRACT

Basaltic lava flows intruded by pre-Cambrian granodiorite and granites comprise the greater part of the Virginia Blue Ridge within the area of the proposed Shenandoah National Park. The flows, extensively altered to epidote greenstone, have been described by Keith in northern Virginia as the Catoctin schist. Greenstone and granodiorite are intruded by the Old Rag granite. All of the preceding rocks are intruded by the Air Point granite, which has been described recently by Jonas in southwestern Virginia. The possibility of the presence of Lower Cambrian flows is discussed. The youngest intrusives are dikes of Triassic diabase.

INTRODUCTION

The new Shenandoah National Park lies in the Blue Ridge of northern and central-western Virginia between Front Royal and Waynesboro, a distance of approximately 65 miles. It includes all the crystalline crest of the mountains. Its boundaries as proposed will extend down the western slopes into the Lower Cambrian sediments, and on the east the area extends as far down as the inhabited heads of the main hollows which is practically to the western edge of the Piedmont province.

The construction of the Shenandoah National Park Highway (Skyline Drive) along the crest of the mountain has made the region accessible and has opened many fresh exposures. The road has been completed (1933) from Thornton's Gap east of Luray to Swift Run Gap east of Elkton.

This preliminary paper summarizes some results of work in this area carried out during the last two summers for the Virginia Geological Survey.[2] It is based on detailed work in about half of the area of the proposed park and some reconnaissance work in other sections.

[1] Published by permission of the State Geologist of Virginia.

[2] This work is part of a geologic survey of the Park area. Dr. Anna I. Jonas and Dr. Arthur Bevan have read the manuscript and made valuable suggestions and criticisms.

It deals briefly with the character of the igneous rocks and especially with their age and relations to each other.

GENERAL CHARACTER OF THE ROCKS

Igneous rocks of intrusive and extrusive origin crop out over the greater part of the area. The mass of the Blue Ridge here consists of granodiorite intruded by granites, mostly cropping out on the flanks of the ridge but in many places extending to the top. Remnants of the old erosion surface at the mountain crest are underlain in many places by thick and extensive flows of basalt, generally altered to epidote greenstone. All of these rocks are pre-Cambrian.

Lower Cambrian sediments appear upon the western slope of the mountains, resting unconformably upon the crystalline rocks; on spurs between deep valleys they even extend to the top of the Blue Ridge. On the western side they are generally found upon the old lava flows, but in certain other sections they overlie intrusive rocks. Narrow, linear, infolded belts of these sediments occur in many places within the crystalline rocks on the crest or the flanks of the mountains.

CATOCTIN LAVA FLOWS

These rocks, mostly flows of metabasalt, have been described by Keith[3] in northern Virginia and named Catoctin schist. They are almost invariably massive in this district. They cap the mountain top and are nearly continuously exposed along the Shenandoah National Park Highway from Stony Man to Swift Run Gap. The belt is essentially continuous along the crest and western side of the ridge but has been worn through in places to expose the underlying intrusive rocks. On the eastern side the streams have frequently cut through the flows, so that intrusive rocks are exposed to the top of the mountain, as at Powell Gap (Elkton quadrangle) at the head of Roach River Valley. The belt is discontinuous between Hughes River Gap and Thornton Gap (Stony Man quadrangle), and granodiorite crops out on the west side of the Lee Highway in Thornton Gap.

An interesting feature of the greenstone in this part of the Blue Ridge is its tendency to show columnar jointing, which may be noted

[3] Arthur Keith, "Geology of the Catoctin belt," *U.S. Geol. Surv., 14th. Ann. Rept.*, Part 2 (1894), pp. 287–395.

in the Stony Man quadrangle between Skyland and Fishers Gap. The development of the profiles of Hawksbill and Stony Man as well as the palisades at Franklin Cliffs is due to rapid erosion in greenstone with a pronounced vertical jointing on the steep western slope of the Blue Ridge. Large columns of greenstone several feet in diameter may be seen in the valley known as "Little Devil Stairs" in the northeastern part of the Stony Man quadrangle.

The basalt is generally altered to epidote greenstone and the secondary minerals are coarse enough to be recognized with the naked

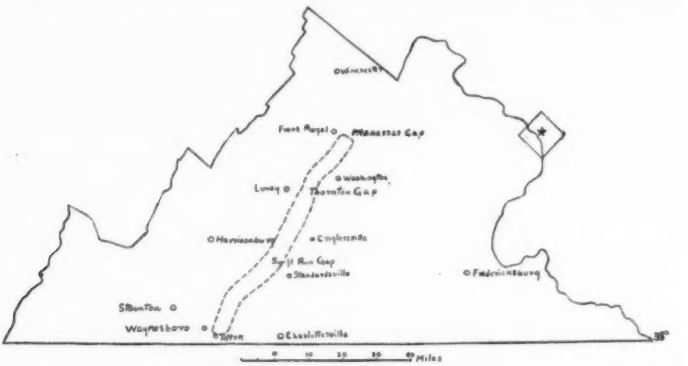

FIG. 1.—Outline map of northern Virginia showing the approximate position of the proposed boundaries of the Shenandoah National Park.

eye. Here epidote greenstone is commonly vesicular and locally scoriaceous, and the vesicles are generally filled with milky quartz and epidote. Some of the quartz is pink. The quartz and epidote may occur singly or together. In some localities red jasper is a common secondary mineral. Small masses of greenish chalcedony sometimes occur. Small masses of green, fibrous asbestos and quartz are also common. Quartz and epidote often fill fractures and epidote may extensively replace the basalt to form epidosite.

No original pyroxene has been noted in thin sections. Plagioclase has been more or less altered to epidote. Secondary epidote and quartz are generally the dominant minerals. Chlorite occurs where the rock is schistose. Magnetite in small amounts is practically always present.

Other volcanic rocks.—Rocks other than metabasalt flows are not found on a large scale in this region, although local occurrences are not infrequent. Pyroclastics are rare. Near Rattlesnake Knob (Stony Man quadrangle) is an agglomerate of greenstone bombs in a fine, ashy matrix of similar material.

At the lower end of "Little Devil Stairs" in the same district is a small outcrop of a reddish-brown breccia largely composed of angular fragments of volcanic rock which are made visible on the weathered surface. A thin section shows fragments with a reddish, glassy matrix which may contain small laths of plagioclase. Some calcite and epidote in grains and patches have developed.

A red and purple flow occurs along the west side of the Blue Ridge between the greenstone and Lower Cambrian sediments. So seldom is it absent that it has been useful as an aid in distinguishing between normal and overthrust contacts along the western side of the range. Its thickness is variable, but may be as great as 100 feet or more. The flow is slaty and frequently amygdaloidal. White oval spots are in places abundant on the cleavage surfaces where quartz amygdules or feldspar phenocrysts have been mashed. In thin section the rock rather closely resembles the one described above, but it is not brecciated. No feldspar is evident in the sections, although there are numerous rectangular rods altered to sericite.

East of Elkton this zone contains a dense purple rock which resembles a partially recrystallized glass and which contains phenocrysts of a basic andesine up to half an inch in length. No thin sections of this facies have been examined.

Geologic age.—The pre-Cambrian age of the Catoctin schist was established by Keith.[4] The Lower Cambrian Loudoun formation unconformably overlies it, occurring less frequently in this district over granodiorite and granite than over the greenstone.

The red flows and associated rocks, described in the foregoing pages, which occur at the base of the Loudoun formation, may be Lower Cambrian. The Lower Cambrian sediments were deposited after an extensive erosion period which completely removed the greenstone flows in some places and exposed granodiorite. It is un-

[4] *Op. cit.*, pp. 327–29.

likely that a thin, pre-Cambrian flow would have been left on the surface of the greenstone after so much erosion.

HYPERSTHENE GRANODIORITE

This rock was carefully described by Watson and Cline,[5] who preferred to call it a hypersthene syenite, although stating at the same time that "the normal facies of the rock should be designated a pyroxene granodiorite." It was classed as hypersthene granodiorite on the *Geologic Map of Virginia*, 1928. In this region it contains too

FIG. 2.—Granodiorite intruding Catoctin greenstone. 1.1 miles east of Swift Run Gap (Elkton quadrangle).

much quartz and too basic a feldspar to be classified as a syenite. Its composition is not constant and in some localities it appears to grade into granite. The basic variety is a granodiorite with pyroxene (usually hypersthene) or biotite.

It is the most widespread intrusive rock in this part of the Blue Ridge, although being generally intruded by younger pre-Cambrian granite, there are few extensive areas which may be exclusively

[5] T. L. Watson and J. H. Cline, "Hypersthene Syenite and Related Rocks of the Blue Ridge Region, Virginia," *Geol. Soc. Amer. Bull.*, Vol. XXVII (1916), pp. 193–234.

mapped as of this type. It forms the core of the range. Very good exposures occur on the western side of the ridge south of Thornton Gap (Stony Man quadrangle). It underlies the Catoctin flows and has been exposed by erosion in the vicinity of Swift Run Gap (Elkton quadrangle) and at many other places.

The rock is mostly coarse grained. Its dark-gray or greenish-gray color is imparted mostly by untwinned feldspar. Blue or smoky quartz occurs and may be abundant. Pyroxene can be recognized in hand specimens. On weathered outcrops the surface of the rock is frequently pitted where less resistant minerals have dropped out. Gullies and washes in roads contain black magnetite sand.

Thin sections show much variation in type of feldspar and amounts of quartz. In basic varieties the dominant feldspar is generally andesine, which frequently fails to show polysynthetic twinning. Orthoclase and microcline may occur. Micropegmatitic intergrowths of quartz and feldspar are common. The dominant pyroxene is hypersthene, but augite frequently occurs; hornblende is present in some specimens; biotite may occur. With increased quartz and potash feldspars, the rock approaches the composition of granite.

Relation to Catoctin flows.—The relation of the intrusives of this region to the Catoctin flows is difficult to determine because exact contacts are not often found. Where they do occur there is often nothing to be observed that can be interpreted certainly as an intrusive effect. The general relation of granodiorite to greenstone suggests that the latter may have been poured out upon an eroded granodiorite surface. On the other hand, the good evidence discussed in following paragraphs, that Old Rag granite intrudes the flows, and the close genetic relationship of this granite to granodiorite, suggest that the granodiorite is the younger.

There is one locality where granodiorite appears to intrude definitely the flows. On the Shenandoah National Park Highway 1.1 miles east of Swift Run Gap, this rock is in contact with typical greenstone. Veins of granodiorite 6–12 inches wide cut the greenstone, in places forming a network pattern. The feldspar of the granodiorite is much altered to epidote and the rock has been injected by the Air Point granite. The original feldspar of the granodiorite appears to be andesine or basic oligoclase.

OLD RAG GRANITE

The most typical and extensive exposure of this intrusive is Old Rag Mountain, an almost inaccessible peak on the east side of the main range and east of Oldrag Post Office (Stony Man quadrangle). The rock is of common occurrence in the Park area, especially on the east side of the mountain. It is a coarse-grained, blue-quartz granite and resembles a facies of the Marshall granite. It is possible that later work may establish their identity. Marshall granite was named and described by Jonas[6] from a place near Marshall, Fauquier County, as ". . . . a pink to green granite and quartz monzonite injected by a pegmatite with blue quartz." It was found to intrude the Catoctin lava flows.[7]

The Old Rag granite is composed of untwinned feldspar and blue or smoky quartz. Where it occurs in large masses, as in Old Rag Mountain, it may be as coarse or coarser than the granodiorite. The feldspar is light gray and is nearly white in very quartzose varieties. The quartz may be distributed through the rock in scattered grains or the grains may be concentrated in discontinuous planes to produce the effect of crude layering.

Microscopic examination shows that the feldspars are orthoclase and microcline, and orthoclase and microcline-microperthite with rods of albite. These plagioclase rods are in places very abundant and exceptionally they constitute nearly 50 per cent of the microperthite.

It is difficult to decide in the field whether certain areas should be mapped as granodiorite or granite. In the upper part of Nicholson Hollow (Stony Man quadrangle) the rock resembles granodiorite in general appearance but is very quartzose and is an intermediate facies between the two types. In some places the intermediate varieties and narrow dikes of granite contain much more hypersthene than the granodiorite.

Relation to Catoctin flows.—Clear-cut examples of the intrusion of Catoctin flows by granite are difficult to find. The best locality discovered so far in the Park area is near the Mission Home in the southern part of the Elkton quadrangle. On the highway east of the

[6] Anna I. Jonas, *Geologic Map of Virginia*, Va. Geol. Surv., 1928. [7] *Ibid.*

memorial to Bishop Whittle, coarse-grained, garnetiferous granite cuts Catoctin greenstone. There seems to be a tendency for biotite and garnet to be developed at contacts of this type. An intermediate rock is commonly produced, consisting of narrow bands of greenstone, biotite schist, and granite. The granite is frequently garnetiferous. In the fields east of the Mission, layers of unaltered greenstone occur in the granite.

The entire Hazel Mountain region southwest of Sperryville (Stony Man quadrangle) consists of biotite schist and garnet-bearing granite which probably represents a similar occurrence.

A greenish-gray biotite or garnetiferous facies which is not visibly associated with Catoctin flows occurs in several localities. At Mary's Rock tunnel near Thornton Gap this type of rock contains albite-oligoclase, orthoclase, and orthoclase-microperthite.

Relation to hypersthene granodiorite.—The granite is closely related genetically to the granodiorite and is probably a differentiate of the same magma. The blue, quartz-bearing granite intrudes granodiorite as distinct dikes or is in closely spaced sheets to form an injection gneiss. Weathering causes the quartzose granitic layers to stand in relief, giving the rock a striped appearance.

Both types of injection can be seen along the Lee Highway in cuts east of Thornton Gap, where the granodiorite contains considerable granite. The section along the Shenandoah National Park Highway west of Mary's Rock tunnel presents many examples of granite dikes and stringers that intrude the granodiorite. The granite in the dikes is mostly moderately fine grained. Stringers and thin dikes of coarse granite of the same type cut all of the other intrusives. Some biotite is developed in the granodiorite near the granite.

AIR POINT GRANITE

This name has recently been applied by Jonas[8] to a pink, orthoclase-microcline granite which intrudes granodiorite in the Virginia Blue Ridge. The name is derived from Air Point on Bent Mountain, Roanoke County. This rock is widespread in the Park area, where

[8] "Grandiorite, Its Intrusion and Replacement by the Air Point Granite in Virginia," *Bull. Geol. Soc. Amer.*, preliminary list of titles and abstracts, Vol. XLIV (1933), pp. 29–30.

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its general character and relations to the other rocks will be described.

The granite has a wide range in composition, lying between a pink, orthoclase-microcline granite with blue quartz to pink granite with epidote; increase in epidote and loss of feldspar produces a quartz-epidote rock. Pink granite is cut by epidote veins and stringers. It may be splotched with red feldspar and quartz.

As shown by thin sections from various localities, potash feldspar, especially microcline, and considerable albite are present. Some intergrowths of microcline and albite may be seen. Epidote is very abundant in some sections, where it occurs in patches and narrow stringers which break across the other minerals. It is usually associated with smaller amounts of chlorite and with patches of hematite and magnetite. Quartz and feldspars are usually more or less strained and granulated.

Varieties and relations to Catoctin flows.—Varieties of this granite are determined by the type of rock intruded, by mode of intrusion, and by degree of replacement. The granite of this district intrudes Catoctin flows and granodiorite. It frequently occurs around the borders of greenstone exposures or between greenstone and granodiorite. Cross-cutting dikes are not to be expected in the greenstone, although stringers of pink granite cut it on the southern slopes of Flat Top Mountain about half a mile west of Wyatt Shiflett Church (Elkton quadrangle).

Pink feldspar is often injected into schistose greenstone to form a pink and green gneiss. Locally the only change effected in the volcanic rock is the addition of red quartz grains. Red quartz may be added in a similar manner to granodiorite. On the east side of Roach River Valley in Bacon Hollow (Elkton quadrangle) greenish granite with pink feldspar and red or purple quartz, in places schistose, occurs next to Catoctin greenstone. All variations from greenstone which contains feldspar and red or purple quartz to pink granite with or without epidote can be seen.

A dark red or purple variety of granite is common at or near the greenstone contact, where it is often fine grained. The deep-red color is due to secondary iron oxide. The greenstone is not much affected, but a fine-grained contact facies of quartz and epidote is sometimes observed.

Varieties and relations to granodiorite.—Intrusive effects are especially noticeable in the granodiorite where the feldspars and the ferromagnesian minerals are replaced by pink feldspar and epidote. Extensive replacements have occurred locally. In places the greenish-gray feldspars of the granodiorite are only partly altered to epidote or they may be completely replaced by epidote and pink feldspar. Such effects are in general local and at a short distance, perhaps only a few feet, the intruded rock may be unaffected. For this reason areas mapped as Air Point granite contain much granodiorite.

Partial or complete alteration of hypersthene granodiorite to epidote and replacement by Air Point granite occurs at many places in the Park area. Near Fishers Gap (Stony Man quadrangle) it occurs in a cut on the highway at the east end of Franklin Cliffs. At the head of Dark Hollow, just east of this gap, the Catoctin flows have been removed by erosion to expose a similar type of rock. Specimens from this locality have the original texture of the granodiorite, due to complete or partial replacement of original feldspars by pink feldspars and epidote.

According to Jonas[9] the Air Point granite ". . . . is, in many places, a coarse pegmatite, and the pink feldspars, orthoclase and microcline replace the more basic feldspars of the granodiorite, in part or entirely, and with the accompanying epidote form a pink feldspar-epidote-quartz rock called unakite." This explanation for the origin of unakite is in agreement with observations made by the writer in the Park district.

Watson[10] described unakite from the Virginia Blue Ridge. The unakite he described as a type of hypersthene syenite. He[11] recognized the vein character of the unakite in Madison County, North Carolina, and believed that some of it may have arisen as ". . . . magmatic segregations or secretions similar to schlieren or possibly pegmatite, some of whose original constituents may have altered to epidote chiefly by hydrometamorphism." Phalen[12] described occur-

[9] *Ibid.*, p. 29.

[10] T. L. Watson, "Occurrence of Unakite in a New Locality in Virginia," *Amer. Jour. Sci.*, 4th ser., Vol. XXII (1906), p. 248.

[11] "Granites of North Carolina," *Jour. Geol.*, Vol. XII (1904), pp. 395–98.

[12] W. C. Phalen, "A New Occurrence of Unakite—a Preliminary Paper," *Smithsonian Misc. Coll.*, Vol. XLV (1904), pp. 306–16.

rences of this rock that he discovered in the Park area on the old Gordonsville Pike east of Milam's Gap at the head of Dark Hollow and west of the gap about half-way between the mountain top and Marksville. He recognized the epidote as a secondary mineral and believed that it was produced from the feldspar and other minerals through the action of percolating meteoric waters, aided probably by dynamic metamorphism.

Geologic age.—This granite is probably the youngest intrusive in the district, with the exception of dikes described below, and is believed to be younger than Old Rag granite, which was probably intruded shortly after the granodiorite. Watson[13] states that the pyroxene syenite and the granites in the middle and northern Blue Ridge regions of Virginia are pre-Cambrian in age. Jonas[14] finds that this granite is pre-Cambrian and describes Lower Cambrian sediments near Montebello, Virginia, and in other localities, which contain fragments of it. Narrow belts of Loudoun arkose and conglomerate which occur over the Catoctin greenstone and the intrusive rocks in the Park district are composed of fragments of all the underlying rocks, and pink feldspar is not an uncommon constituent.

DIKES

Basalt dikes intrude the granodiorite and granite in the region north and west of Sperryville and also less abundantly in other places. They may be seen along the Lee Highway east of Thornton Gap. Many of the dikes have a fresh appearance resembling that of the Triassic intrusives so common in the Piedmont region of Virginia. A dike of this character which shows crude columnar jointing can be seen at the east end of Mary's Rock tunnel on the Shenandoah National Park Highway. A thin section of this rock shows that it is an augite diabase similar in composition and texture to other Triassic intrusive rocks of the state.

[13] Watson and Cline, *op. cit.*, pp. 233–34. [14] *Op. cit.*, p. 29.

EXTENSION OF THE BETHLEHEM, NEW HAMPSHIRE, MORAINE

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ABSTRACT

Moraines at Bethlehem, New Hampshire, on the northwestern slope of the White Mountains have been known for eighty-seven years and were shown by Goldthwait to have been made by a re-advance of the continental ice sheet at the close of the last glaciation. They were formerly known to extend intermittently for 12 miles. This study shows that there are moraines west of those previously known and also exposures of two till sheets, proving that there was a re-advance of the ice over a front of at least 25 miles and possibly 50 miles. These moraines have been correlated with the varved clay studies of Antevs, which showed that the ice sheet re-advanced to the mouth of the Passumpsic River and uncovered it the second time about two hundred and eighty years after the first uncovering. The moraines were formed by a re-advance of the ice during the closing stage of the last glaciation.

INTRODUCTION

The group of moraines in and near Bethlehem, New Hampshire, has been known to geologists for more than three-quarters of a century, having been visited by Louis Agassiz in 1847 and described by him in 1870, after a second visit.[1] He attributed them to a local glacier from Mount Lafayette to the south. C. H. Hitchcock believed that these moraines were formed by valley glaciers from the nearby mountains.[2] Later Upham reported that moraines extended in an almost continuous belt from near the Twin Mountain House westward through Bethlehem to Littleton—a length of about 12 miles—and that they were formed by a local ice cap on the White Mountains.[3] In 1915 Goldthwait made a thorough study of the Bethlehem moraines and associated features and decided that they were formed by the continental ice sheet and not by local mountain glaciers,[4] an interpretation which has been generally accepted. An-

[1] Louis Agassiz, "On the Former Existence of Local Glaciers, in the White Mountains," *Proc. Amer. Assoc. Sci.*, Vol. XIX (1870), pp. 161–67.

[2] C. H. Hitchcock, *Geology of New Hampshire*, Vol. III (1878), pp. 233–43.

[3] Warren Upham, "Moraines and Eskers of the Last Glaciation in the White Mountains," *Amer. Geologist*, Vol. XXXIII (1904), pp. 7–14.

[4] James W. Goldthwait, "Glaciation in the White Mountains of New Hampshire, *Bull. Geol. Soc. Amer.*, Vol. XXVII (1916), pp. 263–94.

tevs believed, from his studies of varved clay and other features, that there was a re-advance of the ice with the formation of a moraine at St. Johnsbury; and he suggested that this moraine might correspond with the Bethlehem-Littleton moraine 15 miles to the east. He also found that the ice uncovered the mouth of the Passumpsic River for the second time about two hundred and eighty years after the first uncovering.[5]

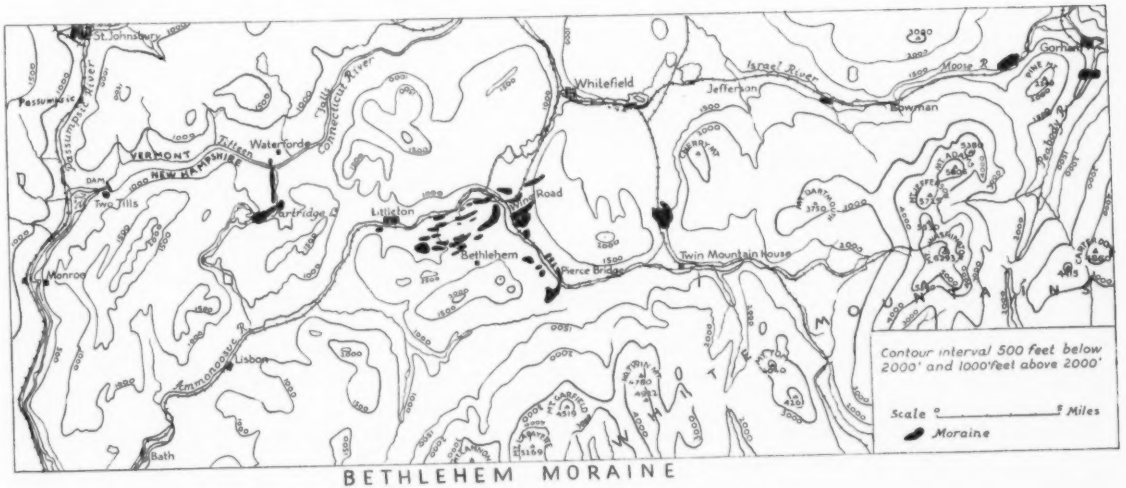
In 1927 the writer began studies of dam sites along Fifteen Mile Falls in the Connecticut Valley and continued these intermittently until 1932. Evidences of a re-advance of the ice, and of moraines which appear to be the westward extension of the Bethlehem-Littleton moraine, were soon discovered. The purpose of this article is to give the results of these studies as regards glacial geology, to show the connection of the features described with the moraines which were already known, and to correlate this information with the varved clay studies of Antevs. First, however, the previously known parts of the moraines will be described, making use of Goldthwait's descriptions[6] and of recent observations by the writer.

The location of the places mentioned are shown on Figure 1. The detailed topography of the areas discussed is shown on the Gorham, Mount Washington, Whitefield, and Littleton quadrangles of the U.S. Geological Survey topographic map. The quadrangle to the west covering the Passumpsic River and St. Johnsbury has not been published.

The morainal features described by Goldthwait extend from the Twin Mountain House westward down the Ammonoosuc Valley to Littleton—a straight-line distance of about 12 miles. These features are in three distinct groups: the main group of moraines in Bethlehem stretching down the valley, but mostly south of the Ammonoosuc River, from a mile east of Wing Road into Littleton; a smaller group of moraines, probably of slightly earlier date, on both sides of the river in the vicinity of Pierce Bridge (Bethlehem Junction); and

[5] Ernst Antevs, "The Recession of the Last Ice Sheet in New England," *Amer. Geog. Soc. Res.*, Ser. No. XI (1922), pp. 83, 84. Also "The Last Glaciation," *ibid.*, No. XVII (1928), pp. 119–21.

[6] Goldthwait, *op. cit.*



BETHLEHEM MORAINE

FIG. 1.—Locations of Bethlehem moraines and associated features

extensive outwash deposits north of the Twin Mountain House and several miles to the east of the others.

Both groups of moraines consist of numerous ridges, knobs, boulder belts, and kettles. There is a prevalent northeast-southwest trend to these features, although many of them appear to be without order. The moraines are composed largely of sand, gravel, and cobbles, with numerous boulders. Sand predominates, but the surface is strewn with so many boulders as to suggest ledges close beneath the surface. The morainal material is, however, thick—probably over 300 feet in places.

The deposits near the Twin Mountain House consist of a kame field 2 miles to the north, a pitted outwash plain extending south from this, and a pair of kame terraces, one on each side of a brook, the eastern terrace connecting with a more irregular, pitted kame plain just northwest of the Twin Mountain House.

THE WESTERN EXTENSION OF THE BETHLEHEM-LITTLETON MORAINE

In 1927 the writer found morainal deposits more than 4 miles west of Littleton in the valley of Mullikin Brook. These deposits are in three nearly connected groups extending along the west wall of the valley from the Connecticut River to Partridge Lake. The moraines consist of kames heaped up 50 feet or more against the steep western wall of this small valley. Midway the moraines extend into the center of the Mullikin Brook Valley.

Partridge Lake is now separated from Mullikin Brook by a kame moraine and empties to the southwest into the Ammonoosuc River, but it seems probable that the preglacial divide was south of the lake and that this part of the valley formerly drained into the Connecticut River. This moraine blocked the valley, however, forming Partridge Lake, and turning the drainage across the old divide to the southwest.

Numerous pits have been dug in the moraine near the river and show that it is composed of till consisting largely of sand, gravel, and cobbles, with a relatively small amount of fine material. Two of the pits and several borings show that this sandy till is underlain by a blue boulder clay. Deposits on the Vermont side indicate that the

moraine formerly crossed the river but that it has been partly destroyed. Both on the New Hampshire side in the township of Littleton and in Waterford on the Vermont side, numerous pits and deep borings show conclusively that there are two sheets of till and that there has been a re-advance of the ice. In places the two till sheets are separated by a layer of sand and gravel, but in other places no separating layer has been recognized in the borings. It is probable that the ice re-advanced across the surface of the till, upon which were small local deposits of sand and gravel, and that in places the upper till was deposited directly upon the lower till. There is no difference in appearance between these two tills and no distinguishing characteristics have been discovered. With the exception of places where they are separated by intervening deposits it is impossible to differentiate them. On the Vermont side of the river is a buried gorge, some 90 feet below the present river level, which is largely filled with till. In places the combined thickness of the two till sheets over this gorge is 180 feet.

No other morainal features were found immediately west of here, but several miles downstream the river flows through a narrow gorge, the high banks of which show a great thickness of till. It has not been possible to determine whether there are two tills here, but part of this till may have been deposited by the re-advance of the ice. This stretch of the Connecticut River flows from east to west, and it seems probable that the front of the ice lay in the Connecticut Valley for some miles west of here and that therefore any morainal features which may have been formed have been destroyed by subsequent erosion.

EVIDENCES OF RE-ADVANCE OF THE ICE IN MONROE

In the town of Monroe 8 miles down the Connecticut River to the west from the moraines just described and at the foot of Fifteen Mile Falls is the Fifteen Mile Falls Dam of the New England Power Association, where numerous exposures, pits, trenches, and borings have clearly shown two sheets of till separated by a layer of sand and gravel. The dam is on the western edge of the Littleton quadrangle.[7]

[7] The dam is shown on the advance sheet of the northern part but not on the present printed edition of the southern part of the map.

Professor J. W. Goldthwait took part with the writer in some of the early investigations of these two till sheets. In October, 1929, they were visited by the party of the New England Intercollegiate Geological Excursion, and a brief note about them was published.[8]

The lower till is a normal, blue boulder clay, but the upper till is somewhat sandier and contains a smaller proportion of cobbles and boulders. The surface of the lower till was more or less eroded, and then a layer of sand varying from nothing to at least 34 feet in thickness was deposited upon it. The elevation of the upper surface of the lower till, where it is protected by overlying deposits, varies from 550 to 589 feet, indicating either that the till was laid down with a very irregular surface or that there was considerable erosion before it was covered by sand. The nature of the sand separating the two tills varies from a fine, silty sand to coarse sand and gravel, and numerous thrust faults were seen in the sand. The upper till is overlain by clay and an upper layer of sand. The clay is absent in places; but where it occurs, it lies directly on the till and below the sand. The lower till either lies directly upon bedrock or is separated from it by a few feet of gravel.

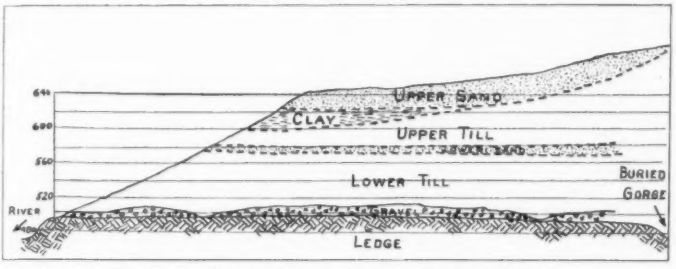
On the New Hampshire side of the river at the dam the bedrock surface is flat, and about 10 feet above the river for several hundred feet. The glacial deposits rise in a high bluff here, and the lower till has a maximum thickness of about 80 feet, but farther from the river the bedrock surface falls off into the buried gorge, and the lower till is more than 100 feet thick (Fig. 2).

The relation of the two tills was best seen in the large pit in the west wall of the valley of Mill Brook just below the dam. This still can be seen, but the exposure is not so fresh as formerly.

The two separate till sheets indicate that there was an advance of the ice sheet here following an interval long enough to permit some erosion and the deposition of a thick bed of sand. No moraine has been found here associated with this re-advance of the ice; and if one was formed, it was probably in the valley and has been destroyed. A continuation of the moraine to the west was sought but was not found, and evidence discovered by Antevs indicates the reason for the ab-

[8] Wilbur G. Foye, "The New England Intercollegiate Geological Excursion," *Sci.*, N. S., Vol. LXX (1929), pp. 454–55.

sence of any moraine west of here. According to him, the varved clay near Passumpsic Station, halfway between the mouth of the Passumpsic and St. Johnsbury, was not again covered by the ice after the first uncovering.[9] It is probable, therefore, that a lobe of ice re-advanced down the Connecticut Valley and another lobe advanced down the Passumpsic Valley to the morainal deposits at St. Johnsbury, but that an area in between was not covered by the re-advance.



FIFTEEN MILE FALLS LOWER DEVELOPMENT
GEOLOGICAL SECTION OF NEW HAMPSHIRE BLUFF ALONG LINE OF DAM

FIG. 2

COMPARISON OF THE UPPER AND LOWER TILLS

The upper till in Monroe, as has been stated, appears to be sandier and to contain a smaller proportion of gravel and cobbles than the lower till. This difference in the tills is borne out by mechanical analyses, the results of which are shown in Table I. The upper till has a much greater proportion of material between 0.1 and 1 mm. (that is, medium to coarse sand) than is generally the case with the lower till, though the proportion of fine material is not very different. The Connecticut Valley in Monroe was occupied by a lake during the retreat of the ice, and it seems probable that the ice re-advanced into this lake, passing over stratified deposits largely sand, and thereby incorporating an unusually large proportion of sand in the upper till.

On the moraine near the Connecticut River in Littleton, New

[9] Antevs, oral communication, Dec., 1933.

Hampshire, and Waterford, Vermont, there is a loose surface deposit consisting of rock flour, sand, pebbles, and cobbles, but without clay. It is a heterogeneous mixture without any evidence of stratification and is probably a till; but it differs in appearance and other characteristics from both the upper and lower boulder clays. It is all brown, in contrast to the bluish-gray of the unweathered boulder clays. This material has been seen only on the moraine, and it may be a till that accumulated on the surface of the ice and from which the clay has been removed.

TABLE I

RESULTS OF MECHANICAL ANALYSES OF TEN SAMPLES EACH OF THE UPPER AND LOWER TILLS

	Percentage Less than 0.01 Mm.	Percentage between 0.01 and 0.1 Mm.	Percentage between 0.1 and 1.0 Mm.	Percentage Greater than 1.0 Mm.
Upper till	8.2	21.9	49.0	20.9
Lower till	6.8	28.2	28.5	36.5

Both the upper and lower tills are oxidized where exposed to weathering, oxidation of the upper till having penetrated about 10 feet from the present surface. Wherever the lower till is overlain by the upper till, the lower till is unoxidized, indicating either that the lower till was not exposed long enough to become oxidized or that, if its surface was oxidized, all of the oxidized material was removed by erosion before the sand layer and upper till were deposited. The contact of the lower till and the overlying sand has been exposed at numerous places, and it seems probable that if the surface of the lower till had been oxidized before the deposition of the upper till, some evidence of this oxidation would have been found. It is probable, therefore, that the interval between the formation of the lower and upper tills was not sufficiently long to allow oxidation to take place.

Bedrock in the vicinity of Fifteen Mile Falls consists of schist with intrusions of diorite and granite, but just west of the mouth of the Passumpsic River is a broad belt of calcareous schist striking N. 30° E. Since this rock is only a short distance northwest of Fifteen

Mile Falls, it seemed probable that it might have supplied calcareous constituents to the drift, and an investigation was therefore made in which more than two hundred samples were tested for lime. In the vicinity of the dam somewhat over half the samples of the lower till were calcareous, while with the upper till the proportion was much smaller. In the pit at Mill Brook, where the contact of the lower till and the overlying sand are well exposed, the lower till was found to be calcareous up to its surface, indicating either that leaching did not take place on the surface of the lower till before it was covered by sand and the upper till or that, if the lower till was leached, all evidence of it has been removed by erosion. The locations of the non-calcareous samples are such, however, that the lack of lime in many cases cannot have been due to leaching, and is probably due to the unequal distribution of calcareous material in the drift.

All the evidence indicates that the interval between the deposition of the lower and the upper tills was short and that both were deposited during the last glaciation.

EVIDENCES OF RE-ADVANCE OF THE ICE SHEET EAST OF THE BETHLEHEM MORAINE

Indications of the re-advance of the ice are found at a number of places east of the Bethlehem moraine. A small ridge, about a quarter of a mile long and from 30 to 40 feet high, which is composed of till and appears to be a moraine, is located in the valley of Israel River, on the south side of the railroad about 3 miles west of Bowman station. This place is in the town of Jefferson, at the north base of the Dartmouth Range, which is the westward extension of the Presidential Range, and is 9 miles northeastward from the outwash deposits near the Twin Mountain House. Farther east along this line of the railroad and at the northwest foot of Pine Mountain is a considerable area of morainal topography in which Moose River has cut a gorge more than 100 feet deep, exposing sand and gravel. Some 3 miles farther east in Gorham, on the Peabody River about a mile above its mouth, a large moraine crossed the valley and has been partly removed by the stream. Varved clay has been found under this moraine, indicating re-advance of the ice over a lake bed. These three developments of moraine are along the north base of the main

range of the White Mountains in line with the northeastward extension of the Bethlehem moraine.

On the northwest slope of Cherry Mountain, between the moraine in Jefferson and the outwash deposits near the Twin Mountain House, several wells have recently been drilled near the highway. These wells passed through glacial drift into bedrock and show that the till is very thick, extending to a depth of 75 feet in one case. No samples had been kept from these wells, and it is not known whether the till is the same for the total thickness, but it seems possible that this unusual thickness of the till may be due to a re-advance of the ice.

These eastward moraines, although separated by a wide gap from the Bethlehem moraine, are along the same general line, and it seems possible that they may have been formed by the same re-advance of the ice. The ice well may have stopped along the northern base of the main range of the White Mountains, which would have offered a very serious obstacle to farther advance. More evidence is necessary, however, to fill in the gaps before these eastern moraines can be definitely correlated with the Bethlehem moraine.

CONCLUSIONS

The Bethlehem moraine had previously been known for a length of about 12 miles. The moraines and other evidence of re-advance of the ice which have been described in the Connecticut Valley are most probably related to the Bethlehem moraine and extend the known length of the line of ice advance to 25 miles.

If the moraines described to the east of the Bethlehem moraine, in Jefferson and Gorham, are associated with it and were caused by the same ice advance, we then have evidence of a line of advance extending from the mouth of the Passumpsic River to Gorham, New Hampshire, a distance of over 50 miles; but before this can be definitely stated, more evidence is necessary to fill in the gaps in the eastern line.

It seems probable that a lobe of the ice sheet advanced westerly down the Connecticut Valley to the mouth of the Passumpsic River, laying down the upper till found near the Fifteen Mile Falls Dam, and that another lobe advanced down the valley of the Passumpsic,

forming the moraines in the vicinity of St. Johnsbury. These moraines thus may have been formed by the same re-advance of the ice which built the Bethlehem-Littleton moraines.

Antevs believes, from evidence obtained from the varved clay, that the ice front stood in the vicinity of St. Johnsbury for at least two hundred years and that it uncovered the mouth of the Passumpsic some two hundred and eighty years after the first uncovering.[10] At the time of Antevs' studies the presence of two sheets of till was not known. The conclusions of Antevs agree, however, with the more recent evidence, and both show that the interval between the deposition of the two tills was short.

The evidence all indicates that these moraines and associated features were formed by an advance of the ice after a short retreat during the closing stage of the last glaciation.

[10] "The Last Glaciation," *loc. cit.*, pp. 119–20.

THRUST FAULTING IN THE EMPIRE MOUNTAINS OF SOUTHEASTERN ARIZONA

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ABSTRACT

Studies in the Empire Mountains southeast of Tucson, Arizona, show an area of large-scale thrust faulting. Adjacent mountain masses also show this type of structure and accumulating evidence indicates that low-angle overthrusts are characteristic of this part of Arizona. In general, the mountains are blocks of Paleozoic limestone overthrust upon Cretaceous clastic sediments which form the intermontane basins. The thrusting has been mainly from the south and east. The compressive stresses were followed by tensional stresses which have produced local, high-angle faults. The age of faulting is tentatively established as very late Cretaceous.

INTRODUCTION

Field studies by the writer and his students at the University of Arizona have brought to light some facts upon the structural history of southeastern Arizona. Detailed mapping of the northern part of the Empire Mountains, about 30 miles east of Tucson, and generalized observations over adjacent areas indicate large-scale thrust faulting, much of which is typical overthrusting. Previous geologic work in this region has emphasized normal or high-angle faulting. The importance of large-scale thrust faulting has been overlooked or the character of the faulting misinterpreted.

GENERAL TOPOGRAPHIC FEATURES

The Empire Mountains are an irregular, north–south trending ridge about 7 miles long, bordered by lower hills and spurs. The location of these mountains with reference to Tucson and other geographic features mentioned is shown on the index map (Fig. 1). Topographically, this local mountain mass is closely related to the much larger Santa Rita Range from which it is separated by Davidson Canyon. The central ridge or the Empire Mountains locally exceeds 5,000 feet in elevation, but the surrounding valleys and detrital-filled basins merge at the south end with the crest of this main ridge to form broad, upland terraces and local hills. This area merges southward into a broad, intermontane basin (Sonoita basin).

The Empire Mountains form a part of the western edge of the Mexican Highland Province as defined by Fenneman.[1] This province is characterized by mountain ranges roughly parallel and separated

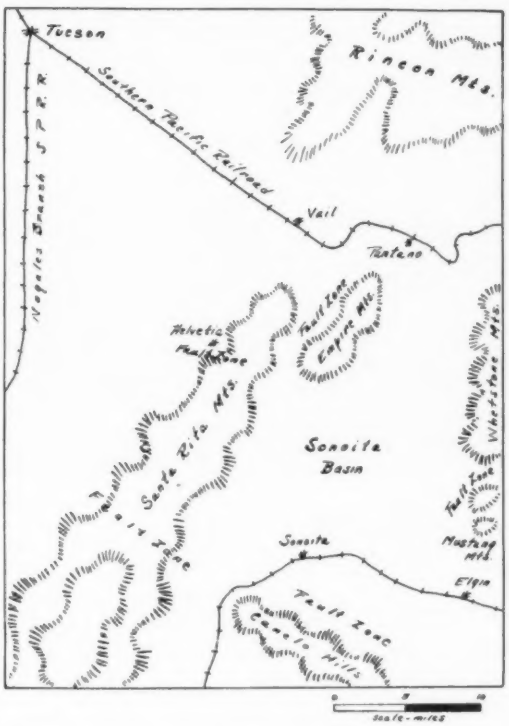

FIG. 1.—Index map showing relation of major geographic and structural features mentioned in the text.

by broad or narrow valleys. The Sonoran Desert Province, which extends westward from this region, differs in the lower elevation of its mountains and the great areas of detritus-filled "bolsons" from which the local mountains jut irregularly.

[1] N. M. Fenneman, *Physiography of the Western United States* (textbook; New York: McGraw-Hill Book Co., 1931), pp. 379, 380.

SUMMARY OF REGIONAL GEOLOGY

A reconnaissance study of this general area was made some years ago by Schrader and Hill of the United States Geological Survey.[2] Detailed work has been done in mining districts of the Santa Rita Mountains[3] and the Patagonia Mountains[4] which lie to the south and outside of the area under consideration. To the north of the Empire Mountains in the Tucson quadrangle, the regionally conspicuous

FIG. 2.—View looking south in the Empire Mountains toward the high, detrital-covered terrace which forms the northern edge of Sonoita basin. The limestone escarpment on the extreme left forms the eastern overthrust block. The position of the fault plane is marked. Photo by Allyn Fisher.

Catalina and Rincon Mountains have been studied by Moore[5] of the United States Geological Survey and previous work has been done in this area by Tolman[6] and others.[7]

[2] F. C. Schraeder, "Mineral Deposits of the Santa Rita and Patagonia Mountains, Arizona," *U.S. Geol. Surv. Bull. 582* (1915).

[3] Private reports, especially on the Helvetia mining district; Master's thesis by Walter Thomas, Univ. Ariz., on the Rosemont mining district (1931).

[4] R. J. Leonard, unpublished manuscript on the Patagonia mining district.

[5] B. N. Moore, unpublished manuscript.

[6] C. F. Tolman, unpublished manuscript.

[7] See especially *Bull. 119* by N. H. Darton: "A Résumé of Arizona Geology," *Ariz. Bur. Mines* (1925); Master's thesis by Robert Hernon, Univ. Ariz.: "Pegmatites of the Catalina Mountains" (1932); also various papers by W. M. Davis and others on the physiography of this region.

The mountains described in the foregoing paragraph are mainly uplifted masses of Paleozoic sedimentary rock with intruded igneous bodies. The detrital-filled basins separating these short mountain ranges are largely underlain by thick sections of Cretaceous sedi-

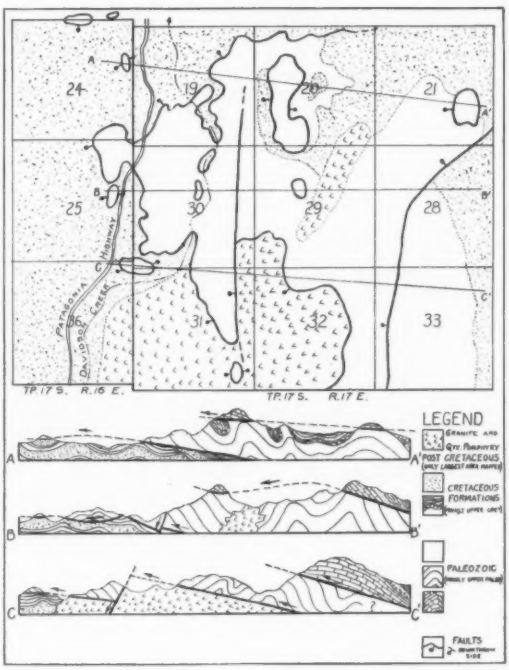

FIG. 3.—Geologic sketch map of northwest part of Empire Mountains (details of geology subject to correction with future field work).

ments with associated igneous rocks. The structural geology is complex but in the main consists of east and southeast tilted blocks of igneous and sedimentary rock that form the mountain masses which are separated from the Cretaceous sediments of the basins by extensive faults on the north and west sides. On the south and east sides of these mountains the sections show transitions to the strata forming the basins (Fig. 3).

PREVIOUS DESCRIPTION OF FAULTING

In his description of the geology of the Empire–Santa Rita Mountains Schraeder states:[8]

> . . . . The Santa Rita Mountains are largely due to faulting. The structure is broadly monoclinal, with a gentle dip to the east. The fault scarp in general faces westward and gives to the west side of the range a general slope of about 1000 feet to the mile. This is considerably steeper than the slope on the east side which in part follows the monoclinal dip. . . . .
>
> The Empire Mountains are characterized largely by the same topographic and structural features as the main range [Santa Rita] from which they are separated by Davidson Canyon. . . . . The fault scarp exposing the edges of the eastward-dipping monoclinal beds that form the west front of the range extends a distance of about seven miles. . . . .

Schraeder maps the above-mentioned fault on the west side of the Empire Mountains as a high-angle thrust with the fault plane dipping to the east.[9] Aside from mentioning this thrust in the text of his report, no details are given.

For the Helvetia mining district in the northwest part of the Santa Rita Mountains he states:[10]

> . . . . The main structural feature is a thrust fault with a gentle dip to the southwest, where contact with the sedimentary rocks runs in an irregular line. . . . . and which has brought the basal granite against the overlying altered Paleozoic limestones for the greater part of the distance. . . . .

In other parts of the text he states that this thrust is of very low angle and of great magnitude. Several cross sections are given.[11]

In the Rosemont mining district on the northeast slope of the Santa Rita Mountains, Thomas[12] mapped a thrust-fault zone along which Paleozoic limestones have been thrust over Cretaceous clastic sediments, the fault plane dipping to the southwest and doubtless forming a part of the thrust zone in the adjacent Helvetia district.

To the north and outside of the area under consideration, along the south base of the Rincon Mountains, the foothills show a general zone of thrust faulting along which the Paleozoic sediments have

[8] *Op. cit.*, pp. 38–39.

[9] *Ibid.*

[10] *Ibid.*, geologic map and cross sections; Pl. 2 and 3.

[11] *Ibid.*, pp. 93–98.

[12] *Op. cit.*

been thrust north and against the metamorphic rocks that form the main mountain mass. Moore[13] has studied and described this faulting.

These observations indicate the general distribution of thrust faulting in the area and especially bring out the fact that, although the faults have been observed in disconnected areas, they all show a general stress operating from a south, southwest, or southeast direction. Hence it is possible that all of these faults are related.

THRUST FAULTING IN THE EMPIRE MOUNTAINS

Twelve square miles in the north end of the Empire Mountains were mapped in detail. This area includes the zone of thrust faulting first mapped by Schraeder. The areal geology and representative cross sections are shown in Figure 3. The thrusting is characterized by two major fault zones. The western zone is a typical low-angle fault, the fault plane of which winds irregularly around the foothills and local valleys. Warping and locally intense folding of the fault plane have produced outliers of the overthrust block and inliers or "windows" where the underlying Cretaecous sediments are exposed through the overthrust Paleozoic limestones. The overthrust block is composed of relatively massive and often marmorized Paleozoic limestones which stand conspicuously above the weaker Cretaceous sediments forming the under block. Excellent exposures of the fault plane occur along the banks of Davidson Creek and its tributaries (Fig. 4). This view shows well the strong local folding of the fault plane together with the contrast in color and erosional features between the overriding Paleozoic limestone strata and the underlying softer and darker Cretaceous beds.

In general, the fault zone is marked by shearing, brecciation, slickensides, gouge, and all the features common to faulting of large magnitude. Near the fault in some localities the Cretaceous sediments have been metamorphosed locally into schistose rocks. Small seepages of water and local mineralization are common along the trace of the fault plane. The deposits of ore in the Montana mine and the California mine are related to this fault, as brought out by Schraeder in his report.[14]

[13] *Op. cit.* [14] *Op. cit.*, pp. 151–52.

The eastern fault zone is the one mapped by Schraeder. The trace of this fault follows along the west base of the main ridge of the Empire Mountains, the ridge forming on its west side a steep, winding escarpment built of massive Upper Paleozoic limestones dipping moderately to the southeast. Part of this escarpment is shown in Figure 2. The horizontal displacement of this fault is less than that of the fault to the west where Upper Paleozoic strata have overridden beds of Upper Cretaceous age. In the eastern fault, massive limestones (probably largely Mississippian in age) have overridden

FIG. 4.—View of the main western overthrust fault plane exposed on the bank of Davidson Creek near the Patagonia highway and Andrade's ranch. The fault plane shows the contact of soft Cretaceous beds with the overlying Paleozoic limestone. Note the folding of the fault plane into an overturned fold with the axial plane dipping steeply to the south. Photo by Allyn Fisher.

thinner-bedded and more intensely folded limestones and clastic beds, which include considerable thicknesses of Pennsylvanian and Permian strata (cross section C–C′, Fig. 3). The several high hills which lie to the west of this main ridge are due in part to cappings of the more massive and resistent limestones of the overriding block, the hills thus forming outliers of the eastern overthrust zone (Secs. A–A′ and B–B′, Fig. 3). The relation of these hills to the main ridge is shown in Figure 2.

Among the numerous, small, high-angle faults, one well-marked normal fault of considerable throw and length strikes north–south along the east side of Sections 19, 30, 31 (Fig. 3). In the southern part of the mapped area this fault causes a repetition of the western over

thrust zone (Sec. C–C′, Fig. 3). In many parts of this general region the writer has found high-angle faulting following the thrusting.

Relative to the age of the overthrusting the following facts have been established. The faulted Cretaceous beds in the western part of the area contain a fauna described by Dr. A. A. Stoyanow, of the University of Arizona, as belonging to the Fort Pierre member of the Cretaceous. The contact relations of the granite (Fig. 3) which is definitely intruded into these Upper Cretaceous beds are shown very clearly in the eastern part of Section 20 and north of Section 24 (Fig. 3). The overthrusting followed the granite intrusions. The faulted contact of the granite and the overriding Paleozoic mass is well exposed on the side of the high hill on the north boundary of Section 31 and at several places along Davidson Creek and its tributaries in Sections 30 and 19. The age of the faulting, therefore, is not earlier than the very close of Cretaceous times. It may possibly be of early Tertiary age or may extend well into the Tertiary, as Moore believes it to do in adjacent areas.[15]

[15] Personal communication.

PEBBLES ROUNDED IN GEYSER TUBES

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ABSTRACT

Fragments of rock that fall into geyser tubes and basins may be rounded by the violent movements of the hot water. This rare type of rounded pebble occurs at the Grand and Turban geysers in Yellowstone National Park.

INTRODUCTION

Fragments of rock may be rounded to make pebbles in a variety of different ways and there are not only different types of rounding but also various other forms. Solution-faceted limestone pebbles have been described by Kirk Bryan[1] and chink-faceted pebbles by C. K. Wentworth.[2] The wind-faceted pebble, glacial-faceted, and other types are well known. This paper describes a new process by which pebbles can be rounded, but the resulting shapes do not differ from ordinary water-worn stones. The field observations were made last summer during a hurried trip through the Yellowstone National Park.

GENERAL DESCRIPTION

In the Upper Geyser Basin near the vent of the Grand and Turban geysers there are many rhyolite fragments which have been well rounded by the action of geyser water. These fragments are mostly from 3 to 5 inches long and from 1 to 2 inches thick. Flat shapes, reflecting the fracture system of the rock, are common. All gradations from rough, angular, irregular fragments, showing no water wear, to perfectly rounded pebbles occur. They are usually covered with a layer of geyserite as deep as $\frac{1}{4}$ inch and commonly thicker on one side than on the other.

ORIGIN

The close association of pebbles of this type with the Grand and Turban geysers indicates that they have been rounded by the vio-

[1] "Solution-facetted Limestone Pebbles," *Amer. Jour., Sci.*, Ser. 5 Vol. XVIII (1929), pp. 193–208.

[2] "Chink-facetting: a New Process of Pebble-shaping," *Jour. Geol.*, Vol. XXXIII (1925), pp. 260–67.

lent action of these geyser waters. During times of eruption, violently swirling water, capable of moving fragments of considerable size, exists in the geyser tubes and in the basins at the surface. Fragments caught in these waters are rounded by attrition against each other and against the walls of the tube. The pebbles must be kept in continuous movement, as geyserite is deposited on all stationary objects, including pebbles. The geyserite covering found on the peb-

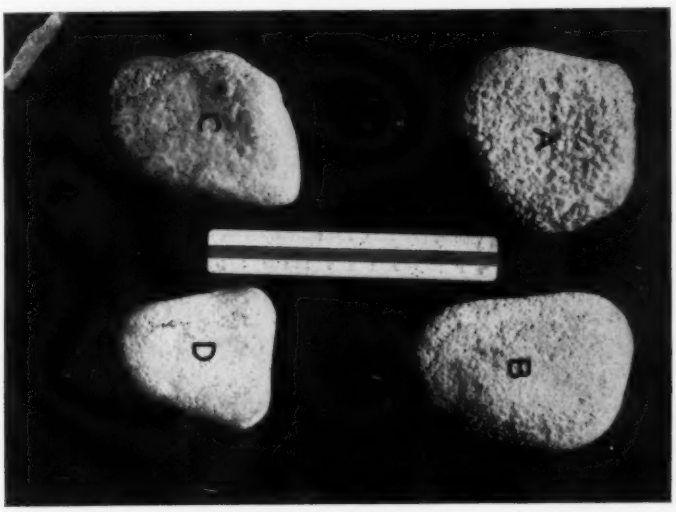

FIG. 1.—Four geyser rounded pebbles. Pebbles *A* and *B* have a coat of geyserite and are considerably rounded. Pebbles *C* and *D* have no geyserite coating and are good examples of the incipient stage, only their edges and corners having been rounded.

bles is secondary to the rounding, and results, no doubt, from a changed position in the geyser tubes and basins at the surface.

Rhyolite is the immediate country rock, but near the geyser tubes geyserite forms a general coating. The pebbles may have entered the tubes from below, torn from the rhyolite walls by the activity of the geysers. It seems more likely, however, that they fell from the cliff of rhyolite which rises to a height of 50 to 100 feet only 15 feet to the northeast of the Grand and Turban geysers. Of late years visitors have frequented the area, and some stones may have been thrown into the tubes by them.

The rate of rounding of the fragments depends on the toughness of the rhyolite (which is somewhat reduced by weathering previous to its fall into the tube), by the distance of the fragment from the most violent action of the geyser, and by the interval, and intensity of eruptions.

DISTRIBUTION

A hurried reconnaissance of the Upper Geyser Basin showed that a few water-worn pebbles occur near other geysers, but that they are less numerous and show less erosion than those near the Grand and Turban geysers. Only a few geysers are so active and powerful as the Grand and Turban, and also near the other geysers there is no ready supply of rhyolite fragments. Boiling pools, which have less violent churning action, cannot be expected to round pebbles, because in them deposition of geyserite on a fragment would be more rapid than wear. It should be pointed out, however, that these water-worn pebbles lying around the geyser tubes can easily be confused with pebbles of geyserite which are being formed continuously by the deposition of siliceous sinter around some small original nucleus.

CONCLUSION

It is quite obvious that this type of water-worn pebble is extremely rare and that probably it will never be found in stratified rocks, yet it seems worth while to put on record a type of pebble which, but for the coating of geyserite, might easily be mistaken for ordinary water-worn kinds.

THE ORIGIN OF ICE CAVES

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ABSTRACT

The occurrence of ice in caves is given together with a statement of some common theories of its origin. A diagram is presented, and the writer's theory, as substantiated by tests made in such caves in Idaho and New Mexico, shows that the origin of the ice is based on free circulation of air in winter and a restricted circulation in summer.

A geologist was questioned by the writer as to what theories were offered to explain the occurrence of ice in certain caves. The reply was that this would be a good problem to work out by making tests in such caves. A few years later the writer found himself in Shoshone, Idaho, 10 miles from which is located one of the world's largest ice caves. A dozen or more trips were made to this cave and a number of tests performed at all seasons of the year over a period of four years. The circulation of the air in the cave was well established by these studies, and this led to an explanation of the persistence of ice in the cave throughout the year. Two similar caves were located later in New Mexico, tests were conducted there, and practically the same conditions were found as existed in the Shoshone cave.

Many popular fallacies are encountered in obtaining information concerning ice caves. One of the commonest is the statement that the ice melts in winter and freezes in summer. Another is that the freezing action is due to ammonia in some form, an idea derived from the prevalence of ammonia gas in ice plants and not from actual occurrence of it in any cave that has been studied. Yet another belief is that the freezing is due to an alternate expansion and contraction of the air within the cave. Stearns,[1] who examined similar occurrences of ice in the craters of the Moon district in Idaho, dismisses the question with the statement that "water . . . . is frozen by cold circulating air." This statement, though undoubtedly true, does not explain why there should not be an equal circulation of warm air in

[1] H. T. Stearns, "Craters of the Moon National Monument of Idaho," *Idaho Bur. of Mines and Geol. Bull. 13* (1928), p. 18.

summer which would melt the ice. As the mean annual temperature of the Shoshone region is about 43° F, if the circulation in summer were the same as that in winter there would be no holdover of ice through the summer. Also, several other caves exist in the Shoshone region, located either in the same basaltic flow or in similar ones; but no ice remains through the summer in any of them.

The Shoshone ice cave is a portion of one of the large subsurface lava tubes in the Black Butte flow, which is one of the most recent lava flows on the Snake River plain. The lava tube has collapsed in most places, but the ice occurs in a place where the roof is intact. The cave is about 250 feet in length, with a maximum width of 60 feet and a height half as great. The ice commences near the entrance and covers the floor for the entire length. Toward the back of the cave the roof also is covered with a coating of ice, particularly in winter; and the cave ends in a wall of ice which completely fills the underground channel. It is not known how much farther this wall of ice extends, but several drill holes have failed to pass through it. The entrance of the cave has been formed by the collapse of a part of the cave roof. One enters the cave on hands and knees and descends a steep ice slope before coming to the smooth, level floor of the cave.

A number of tests with smoke were made by the writer in order to determine the air circulation at different times of the year. The theory submitted is as follows: The entrance of the cave is at *D* (Fig. 1). The letter *A* indicates a small air passage, the exact location and length of which are not known and probably could not be determined. It is believed to be a connection made through the collapse of the lava tube some distance back of the ice. The basalt is honeycombed with cracks facilitating air circulation. Letter *B* represents the basin, about 50 feet deep, through which entrance is made to the cave. This basin faces south, and the winter sun strikes a large part of it. Its sheltered position gives it a temperature in winter a number of degrees warmer than exposed points like *A*. Suppose that the temperature on a certain winter day is 20° below zero at *A* and zero at *B*. In such a case an air circulation would be set up from *A*, through the cave, and out at *B*. When water freezes, heat is liberated; so if water froze in the cave, the heat liberated would help warm the air passing out through the entrance *D*. Such a circulation

would freeze ice in winter and would draw the cave full of very cold air. That this circulation actually does exist during the winter was determined by the writer, who made a number of tests with smoke. The variations of temperature were also tested by the writer on several occasions.

Now let us compare the conditions during the summer. The summer sun is more nearly vertical, and part of the basin *B* is sheltered from the direct rays by the overhanging cliff. On the other hand, vent *A* is exposed to the direct rays of the sun for a longer part of the

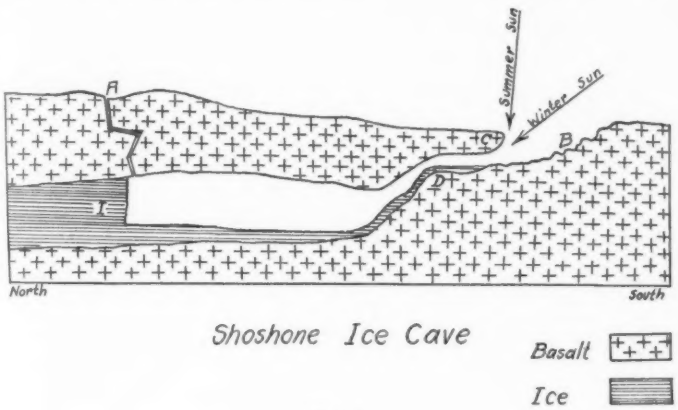

FIG. 1

day. On such a day the temperatures at *B* and *A* would probably be nearly the same, with *A* possibly the warmer. Any air circulation in summer would be slow, owing to very small differences in temperature. It is even possible that the circulation would be from *B* to *A*. The warm air entering at *B* comes in contact with the ice at *D*, melts some of it, and thereby loses heat, becoming chilled nearly to the freezing point. As shown by tests the cold air collects in the cave and has a marked tendency to remain there.

The cave has a temperature several degrees lower in winter than in summer. A well-defined circulation from *A* to *B* was noted in winter, but seemingly there is no circulation at all in summer, with the exception of a few eddy currents between *C* and *D*. Some of the

ice near the entrance melts in summer, but this melting stops near the middle of the cave and the ice wall *I* is always intact in summer or winter.

The circulation system, coupled with the fact that the mean temperature of the Shoshone region is about 43° F, offers a means of explaining the occurrence of ice in this particular cave. Later the writer visited the smaller ice cave at Grants, New Mexico, and found that the same conditions prevail. Information on the ice cave near Flagstaff, Arizona, suggests similar conditions. It is a notable fact that all of these caves occur in basalt and in localities which have a comparatively low mean annual temperature and very cold weather in winter. No ice caves have been found except in regions where freezing temperatures prevail in winter. The writer will appreciate further information on these caves, or on other ice caves, as he wishes to make a further study of these phenomena.

REVIEWS

Igneous Rocks and the Depths of the Earth. By R. A. DALY. New York: McGraw-Hill Book Co., Inc., 1933. Pp. 598; figs. 190. $5.00.

When Professor Dalv's book on *Igneous Rocks and Their Origin* was published in 1914 it aroused a considerable storm of criticism and defense. It nevertheless stimulated a prompt attack on certain igneous problems, and this resulted in real progress. The present volume contains some revised chapters of the original, which is now well known (though not reviewed in these pages).

This book is essentially new but it follows the broad outlines of the older one and, like the older one, it presents certain hypotheses that are not generally accepted. The treatment here, however, is less dogmatic, and there is a skilful form of expression that is less likely to stir up criticism. Some opposing hypotheses are given a fair review and the discussions of controversial matters lead up to questions rather than to assertions. There are many pages in the book where the author gives the impression that he has written as an impartial judge rather than as an advocate. There still remain, however, many fundamental ideas which are vigorously advocated, apparently with the assumption that other petrologists may with equal propriety advocate the contrary hypotheses.

The effort of the author is to present his selected group of ideas about igneous rocks, clearly and fully as a coherent group—an eclectic hypothesis. This is done, as he says, not with the purpose of advocating the particular scheme, but of presenting the scheme in adequate form. "If any scheme is worth consideration at all it is worth a book for its unfolding." Petrologists may hope that some other hypotheses will soon be presented with as much care and clearness as this one has been; but few of them are willing to make the effort. It may be a long time before we have any more than minor attacks on certain phases of the problem.

The book is divided into three parts. Part I: "Leading Facts," is a compilation of the valuable up-to-date sort for which the author is well known. Part II: "A General Theory," considerably revises the theories of the older book, but retains the broader ideas. Part III: "Applications," considers the probable origin of igneous rocks of the several clans,

and adds a final chapter on "Principles and Projects," most of the projects being presented as stimulating questions.

Professor Daly frankly states in his Preface that "at present no comprehensive work on petrogenesis can be other than a report of progress of its author's own synthetic thought on the broad subject." The more vital changes from the older book include the following:

> New doubt concerning the relation of the earth's contraction to mountain building and to the ascent of igneous melts from depth; new emphasis on at least moderate horizontal displacement of large parts of the continental crust over the earth's body; new emphasis on magmatic stoping and the correlated abyssal pure melting of rocks . . . . ; less emphasis upon liquid immiscibility in magmas; more attention to the contrast of early pre-Cambrian time as against Paleozoic and later time . . . . ; new stressing of the fact that no one process can explain the diversity of the igneous rocks.

Each of these changes will seem to some petrologists like new light on a troublesome problem, and to others like a retrogression in geologic theory. Each has been the subject of active discussion, but a book review is not the place for a continuation of such discussions.

Taken as a group these changes seem to be unimportant compared to the main hypothesis presented in the book. While such changes may be credited to the author's progressive thinking, the reviewer feels that a more fundamental change was to be expected; namely, in the underlying assumption as to the condition of the inside of the earth. No such change appears. Professor Daly says the chapters of general theory, though largely new, are "based on the fundamental assumption of the older book: that the crust of the earth is real, relatively thin, and resting upon a vitreous, highly rigid, but extremely weak, basaltic shell, continuous around the globe."

There are perhaps a dozen evidences and arguments for a liquid condition of the inside of the earth; and about as many against it. All these, for and against, are readily answered by counter evidence and argument, *except one:* namely, the peneplains. Dr. T. C. Chamberlin long ago called attention to the process of baseleveling and its fatal opposition to the older theories of a liquid earth. Professor Daly dismisses the evidence (p. 198) with a four-line footnote. A few pages of discussion might have so weakened the fundamental assumption of the book as to make some chapters hardly necessary.

It is therefore on the basis of an earth essentially solid that the reviewer believes a different petrologic hypothesis should be built. If the present book stimulates someone to make such a comprehensive statement we

shall have at least two books expounding the two hypotheses. And Professor Daly may be credited not only with the presentation of one, but with the incentive for the presentation of the other.

The book is clearly written, well printed, and effectively illustrated with material from many recently described districts. It shows evidence of a great amount of work, presented with brilliance and originality.

Not as a textbook but as a basis for discussion, the book is recommended, perhaps for an advanced seminar where the ideas are compared with those of other writers. Every practicing petrologist should read and critically ponder over it. Whether he agrees or not, his interest will be stimulated by the author's enthusiasm and the tonic quality of his suggestions.

F. F. GROUT

Foraminifera: Their Classification and Economic Use, 2d ed.; and *An Illustrated Key to the Genera of Foraminifera*. By JOSEPH A. CUSHMAN. Cushman Laboratory for Foraminiferal Research, Special Publications Nos. 4 and 5. Sharon, Mass., 1933. Pp. 349; Pls. 71. $5.00.

The first edition of Cushman's *Classification*, published in 1928, was described by the reviewer in this *Journal* as "the judiciously abridged summary of the significant results of twenty years of research on the Foraminifera by one who had appreciated their significance . . . . long before" there was such a position as "micropaleontologist" in the petroleum industry. Although "nearly thirty years of experience" must now be substituted for the "twenty" of the foregoing appraisal, the second edition of this important work even more richly merits the quoted commendation.

The new physical makeup is much more pleasing from every point of view, and the text alterations and plate additions represent important improvements from the average student's standpoint. Perhaps the most significant forward step, however, is the issuance of the work in two parts. The first consists of text and plates of explanatory character concerning the morphology and relationships of the Foraminifera. The second is an illustrated key to the genera and families of the order. The latter book is of a convenient size for ease of handling, and is especially suitable to be used in connection with a study of the text of the former. The plates illustrative of the genera uphold the usual high standard set by Dr. Cushman and Miss Margaret Moore, his illustrator. Moreover,

these plates for the first time lack the customary, but space-wasting, margins. Nevertheless, with their effective black backgrounds and their enlarged size, the plates achieve at once an increased economy and a surprisingly artistic appearance.

The systematic descriptions make up about 240 pages, and define 47 families, including a few more than 500 genera. The classification varies little from the one used in the earlier edition, with the exception of the inclusion of the families Victoriellidae and Pegidiidae and the descriptions of approximately a hundred additional genera which have been added. Dr. Carl O. Dunbar contributed the chapter on the Fusulinidae, and Dr. T. Wayland Vaughn the one on the Orbitoididae. Finally, the already excellent Bibliography has been expanded to 37 pages, and includes works issued as late as July, 1933.

Those who read Cushman's *Classification* with Galloway's *Manual* open before them will find not a few categoric statements in the one work which are equally flatly, one might almost say blandly, denied in the other. Most of these diametrically opposed views result from the fact that Cushman believes that "calcareous tests develop directly from arenaceous ones," whereas Galloway is equally completely convinced that the arenaceous wall is degenerate, and is developed from the other types. The average student, therefore, who is fortunate enough to have access to both these works may find himself somewhat confused by their conflicting testimony. To the experienced worker, however, this not unnatural disagreement should prove not bewildering, but stimulating, for it points the way to new researches without at the same time destroying the usefulness of the reference works.

Cushman's excellent publications, which now should be more widely used than ever as textbooks, have a few faults which to the reviewer seem common to all privately issued publications. These usually involve minor editorial errors and slipshod proofreading. In fact, some of the obvious errors of the first edition carry through unaltered to the second, in which corrections inserted by pen and ink are nearly as common as in its predecessor. Furthermore, the names of the authors of families and subfamilies are not given, and the magnifications of the figures in the second edition are stated as the same as for the first, though the illustrations actually are considerably enlarged. These are the typical minor errors of omission and commission which usually are picked up when a manuscript must come under the close scrutiny of a number of critical editorial eyes before it finally gets into print. In fact, the great wonder is that a work from concept to cover so much the product of one man should be so free

from the type of error just described; for this latest of many contributions we, therefore, renew our thanks to Dr. Cushman for his services to paleontologists in particular and to geologists in general.

CAREY CRONEIS

An Introduction to the Study of Fossils. By HERVEY WOODBURN SHIMER. 2d ed. New York: Macmillan Co., 1933. Pp. 496; figs. 207. $4.00.

First published nearly twenty years ago and having in the meantime gone through a number of reprintings, this popular text has been issued at last in a completely revised edition. The new volume, which seems thinner and more graceful than its predecessor, nevertheless has about 50 more pages than the original. This increase results from the addition of a number of new illustrations and the insertion of sections at the end of the chapters summarizing the evolution of the phyla and indicating their importance as rock-formers.

Naturally it is impossible to compress the entire field of paleontology into a scant 500 pages and please everyone with the result. But in the selection of the vast amount of important data which had to be omitted Dr. Shimer has done a very good job. How difficult a task it must have been may be judged from the fact that the plants are discussed in 46 pages, the invertebrates in 264, and the vertebrates in 88. This allotment is also a fairly good criterion of where the center of emphasis lies. In addition to the sections listed above, there is also a valuable chapter of 41 pages on the general subject of fossils.

The new edition of Shimer's *Introduction to the Study of Fossils* probably will enable this text to maintain its leadership in the field of elementary training in general paleontology.

C. C.

Elements of Optical Mineralogy, Part II: *Descriptions of Minerals.* 3d ed. By ALEXANDER N. WINCHELL. New York: Wiley & Sons, 1933. Pp. xviii+459; figs. 362. $6.00.

This new edition of one of the best descriptive mineralogies is welcome, although it has been but six years since the last one appeared—concrete evidence of the rapid advance of the subject under the impetus of numer-

ous quantitative microscopic studies. This edition has thirty-five more pages and twenty-nine more figures than the last edition; a number of the older figures, however, are redrawn with improvements. Beyond these differences and bringing the data up to mid-1932, the only striking change is in the classification of the silicates, which is now according to the well-known outline formulated by Professor Bragg. The reviewer considers this a great improvement over anything previously offered, but Professor Winchell has used this classification for some of the silicates and his old one for the others ("silicates not yet classified by x-ray studies"). Such splitting of silicates is to be deplored. It may be too soon to follow the Bragg plan in so complete a work; but whatever classification is used, all silicates belong in it. It would seem that silicates of doubtful structures and formulae could be placed on chemico-crystallographic relationships, in appendices to the seven major divisions of silicates based on x-ray studies, rather than lumping them at the end. Thus the "clay-minerals" as well as the brittle micas are badly split; vermiculites are not in the division with the micas. Moreover, the crystalline forms of SiO_2 belong not with the oxides but with division 7 of the silicates, as is suggested by the table on page 173. It would seem desirable to put the scapolites closer to the plagioclase feldspars, rather than using them to separate two series of the feldspathoids. Pectolite and wollastonite belong together, and probably they with rhodonite could be placed to advantage near the pyroxenes.

Sulphur is "less abundant in coal deposits" (p. 16). The reviewer has never seen sulphur in coal, nor any authentic reference describing it there, though its occurrence in several lignites seems well established. On page 108 is stated "so-called sulphur in coal may be copiapite." Normal iron melanterite (not in the book under review) is commonly found in small amounts in Mississippi valley coal mines. The statement that ozocerite is "found in seams in coal" (p. 18) is very questionable.

The book lives up to the publishers' high reputation for quality; the number of typographical errors noted is very small considering the type of material. Professor Winchell has greatly simplified the work of the teacher of optical mineralogy. The value of the work is so great that controversial matters of classification are of little significance.

D. J. Fisher

Grundriss der Mineralparagenese. By F. ANGEL and R. SCHARIZER. Vienna: J. Springer, 1932. Pp. 293. RM. 19.80 (bound).

The need for a reasonably comprehensive modern work on the origin and association of mineral matter is very great. This book gives a good deal of information of this sort, but it is buried in a mass of prose describing physical (especially optical) and chemical properties. Much controversial ground is covered, often very briefly; the material is of greatly varying quality. In general, formulas derived by X-ray students are used, but entire consistency in this respect is not obtained; e.g., the amphiboles are classified as metasilicates. The scope is wide, as shown by the presence of over thirteen hundred names, including many doubtful species in the mineral Index alone; this omits, however, the numbers of many pages on which certain minerals are mentioned. Outstanding omissions include the lack of all but very brief tables, and the entire absence of references and illustrations. In general the book is too involved and difficult for any but advanced students and professionals in mineralogy, petrology, and economic geology, but such will find much worth-while information present, though to these the lack of references will be exasperating.

The book, written from the petrogenetic point of view, quite properly deals rather briefly with petrogenesis itself. Its three sections are headed "Rock-forming Minerals and Their Histories" (153 pp.), "Ore Deposit Minerals" (97 pp.), and the "Bioliths" (23 pp.). The first is subdivided into "Primary Minerals and Rocks" (60 pp., including igneous rock and pegmatite minerals), and "Secondary Minerals and Rocks," including hydato- (metasomatic replacement and leaching products), contact-, dynamic-, injection-, and pyro-metamorphic minerals.

D. J. FISHER

Handbuch der Geophysik. Edited by B. GUTENBURG. Berlin: Verlag von Gebrüder Borntraeger, 1933. Vol. II, Part III: Pp. xvi+237, figs. 62; Vol. VII, Part I: Pp. v+252, figs. 54. Individual parts, RM. 42; by subscription, RM. 28.

Part III of Volume II includes *The Surface of the Earth,* by E. Kossinna; *The Petrographic Structure of the Earth's Crust,* by S. Rösch; and *The Chemistry of Meteorites,* by G. v. Hevesy. The first section contains a wealth of data on the form and distribution of land and water masses on the surface of the earth, as well as much information on the form of the sea bottom. Condensed descriptions are given of the main features of the

continents, and the contribution closes with a consideration of the changes in the earth's surface due to endogenic and exogenic forces.

The section by Rösch begins with a discussion of the elements composing the earth, and rapidly succeeds to a detailed consideration of mineral chemistry, in which the main groups of rock-forming minerals are discussed, including the properties of numerous binary and ternary sytems. A detailed treatment of rock textures and structures is followed by descriptions of igneous, sedimentary, and metamorphic rocks. In this treatment rock classification is deservedly given considerable space, and the various proposed systems are reviewed.

Professor v. Hevesy's contribution covers quite adequately the classification and composition of meteorites, with a consideration of the light shed by them on the question of the earth's composition.

Part I of Volume VII includes *The Ice of the Earth*, by Hs. Hess; *Lakes*, by W. Halbfass; and *Underground Water*, by W. Koehne. The first part of Hess's contribution describes the properties of ice and show, and follows with a discussion of glaciers. Here are included structures, crevasses, and other characteristic features. A detailed treatment of the theories of glacial movement is included, and the author inclines toward plastic flow as the principal factor. A mathematical theory is developed in which are included questions of velocity of flow as well as of the distribution of energy within the ice mass. The discussion is a well-formulated attempt to frame a complex phenomenon in precise terms. The section concludes with a description of the distribution of ice on the earth's surface. It is interesting to note that approximately 85 per cent is distributed about the South Pole of the earth.

Professor Halbfass' discussion of lakes considers them from the geographic, geologic, morphologic, and hydrologic viewpoints. The hydraulics, thermics, and chemistry of lakes are treated in much detail. A section on the optics of lakes is included, in which are considered the transparency and color of the waters.

In the section on ground water, Koehne takes up the laws of flow under various conditions. The discussion is largely mathematical, and considerable space is justly devoted to flow in sands. The mathematical treatment is well presented, and the author makes a particular point of clearly defining each symbol used. This treatment is followed by a consideration of capillarity and of the influence of gases on the movement of the water. A final section describes the dependence of ground water on climate, and includes brief discussions of each of the main climatic types.

The preceding publications reviewed represent part of a series of ten

volumes, each containing two or more parts. In an earlier review (*Jour. Geol.* Vol. XLI [1933], pp. 99–101) a general description of the purpose and content of the volumes is given. The parts are uniformly well printed and well illustrated, and the complete set will form an important reference work for geologists in all branches of the science.

W. C. KRUMBEIN

Mineral Deposits. By WALDEMAR LINDGREN. 4th ed. New York: McGraw-Hill Book Co., 1933. Pp. xxvii+930; figs. 333. $6.50.

The fourth edition of this standard textbook on economic geology presents a partly revised text and the addition of some new and improved illustrations. The same excellent organization of material that characterized earlier editions of the book is retained. Several chapters have been re-written, but, despite the addition of much recent material, the size of the volume has been kept within its former limits. Users of the text will appreciate this advantage.

W. C. KRUMBEIN

Handbuch der Palaeornithologie. By KALMAN LAMBRECHT. Berlin: Gebrüder Borntraeger, 1933. Pp. xix+1024; figs. 209; pls. 4. Rm. 115.

The birds are a group which have been in general neglected by the student of fossils. The writer or teacher in the field of paleontology usually treats of the Mesozoic toothed birds and a few of the more spectacular flightless types and then hastily passes on to other fields. This neglect is due in some degree to the comparatively small amount and fragmentary nature of fossil-bird material. In greater measure, however, it is to be attributed to the specialized nature of the subject. Avian osteology is a subject with which few ornithologists, even, are conversant and few workers on fossils of other groups have attempted to interpret fossil-bird remains. The literature is widely scattered and confusing.

All this is changed through the appearance of Lambrecht's *Handbuch*. In its thousand and more pages we find a comprehensive summary of the entire field based on an exhaustive investigation of the literature and rendered additionally valuable by the author's first-hand knowledge of the majority of known remains. For the reader not familiar with the bird skeleton, the way is paved by an introductory section (pp. 4–57) on avian osteology. About half of the volume (pp. 58–649) is occupied by a

systematic section, with accounts of every described species of fossil bird, and full references to the literature. For all the more important groups there are general discussions of phylogeny, relationships, and adaptations. For each order there is an introductory bibliography of the osteology of recent forms, and a concluding tabular summary of the geographical and geological distribution of fossil types. Pages 650–792 are occupied by a stratigraphic section listing all faunas. A final section (pp. 793–920) treats of general paleontological and biological matters, such as fossilization, tracks, fossil eggs, guano as a geological phenomenon, adaptations, pathology, the origin of birds, and the "ratite" problem.

Nearly fifty pages of indexes—of topics, localities, horizons, museums, authors, illustrations, and taxonomic terms—add to the usefulness of the book.

For no other group of vertebrates have we any work comparable to this remarkable contribution to avian paleontology. Lambrecht all too modestly calls his work a "first sketch" for a treatment of the subject in the proposed Schindewolf-Borntraeger handbook of paleozoölogy. It will, however, be a difficult task for the other writers in this series to live up to the magnificent example set by the present volume.

A. S. ROMER

Man and the Vertebrates. By ALFRED S. ROMER. University of Chicago Press, 1933. Pp. 427; figs 278. $3.00.

The book is an introduction to the physical man; and when it has been read one has an explanation of how he came to have his many structures, each of which is a derivative from sone one of the varied habitats in which his ancestors lived. The first part of the book is historical, and, beginning with the origin of the vertebrates in the water, shows how the fishes first became masters of the water; and then, as they multiplied, became adapted for occupying all the varied habitats in the sea and streams. Then the author takes up all the fundamental modifications which were involved in the change from aquatic to land life. The first land forms are amphibians, still having to go back to the water to breed, and for at least a part of their food. Then came the reptiles, which solved the problem of breeding on land, and then moved into every possible land habitat, as well as flying in the air, and in various cases went back to the water again. It is a vivid picture. Next the mammals developed new types of teeth, and took to feeding on the new types of vegetation, fruits, nuts, grass, etc., and in the end almost completely replaced the reptiles.

Finally, during the ice age, man emerged, and his changes and development into the present-day races are traced.

After treating the progress of the vertebrates historically, there are chapters in which the soft organs are taken up to show how they also were developed through the various groups of earlier forms. Finally, there is an outline of the embryonic development of man.

The book is illustrated by clear figures and diagrams and will appeal to a much wider public than formal students: for, though it covers a wide field of facts, it has a clear and coherent line of thought throughout.

F. B. LOOMIS

On the Mineralogy of Sedimentary Rocks. By P. G. H. BOSWELL. London: Thomas Murby & Co., 1933. Pp. ix+393. 21*s*.

Professor Boswell has on several occasions given to the students of sedimentary petrology excellent historical reviews of the development of that subject and has also included in these summaries very helpful bibliographies and abstracts. He has now assembled the results of his several earlier papers in a single volume and has brought his bibliographic references up to date. One thousand and twenty-five papers are listed and each is separately abstracted. In addition, forty-one general works are listed. The Bibliography and abstracts constitute two-thirds of the whole volume.

The balance of the book is mainly a series of eleven essays, each a chapter in length, on certain aspects of the mineralogy of the sedimentary rocks; namely, history of investigation, the individuality of sediments, stability of detrital minerals, minerals as clues to source of sediments, petrographic correlation, shore and dune sands, deep-sea sediments, authigenic minerals, clays and clay minerals, detrital minerals, and the origin of metamorphic rocks. They are, for the most part, historical reviews, though Professor Boswell has added many items from his own experience. These essays enable an investigator to orient himself and gain a general perspective of his field, to know the present trends in the science as well as its present state of development. The reviewer found them very stimulating and suggestive of many possible lines of research.

The book also contains six useful indexes; namely, a general index, an index to stratigraphic horizons, to localities, to mineral species, to figured minerals, and to technique of investigation.

The extensive Bibliography and abstracts alone make the volume indispensable to sedimentologists.

F. J. P.

Syllabus and Laboratory Manual for Geology. By HERBERT P. WOODWARD. Ann Arbor, Mich.: Edwards Bros., Inc., 1933. Pp. 47; detachable pls. 19; pls. 14. $1.00.

This manual, designed for elementary students in geology, outlines a well-organized course of study in which exercises and problems play a prominent part. The subjects treated include common minerals; igneous, sedimentary, and metamorphic rocks; interpretation of topographic and geologic maps; construction and interpretation of structure, columnar and restored sections, and block diagrams; division of geologic time; paleobotany, vertebrate and invertebrate paleontology; and historical geology with special emphasis on general faunal aspects and paleogeography.

The manual is double column, lithoprinted with detachable pages of exercises. The print is easily read and the number of typographical errors small. The maps and diagrams are well executed.

Of particular interest is the method of stimulating the student's interest by presentation of actual geologic problems from the point of view of the professional geologist. It is regretted that such a large proportion of the examples are drawn from the Middle Atlantic states, although with some revisions and omissions the manual might be used in other sections of the United States and Canada. Teachers of elementary geology will find this manual a worth-while addition to their individual libraries and worthy of consideration for class use in the laboratory.

GORDON RITTENHOUSE

Catalogue of Small-Scale Geologic Maps, Part I: *North America, Central America, and the West Indies.* By WALTER H. BUCHER and STAFF OF CONTRIBUTORS. Washington, D.C.: National Research Council, 1933. Pp. vi+132. $1.00.

The great need of knowing what maps are available for geologic studies was recognized by the Committee on Tectonics of the National Research Council and the preparation of a catalogue of such maps was undertaken as one of its projects. The titles of geologic maps contained in this catalogue were collected to form a working basis for broad, regional studies. They are intended primarily as a foundation for synthetic work on world-tectonics. But they will be found useful by all who are concerned with regional studies in physical geography, paleogeography, and economic geology. Each entry includes the author of the map, the area covered, scale of map, and place and date of publication.

R. T. C.